Drop Placement Error Analysis for Ink Jet Deposition

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Abstract

Most industrial and commercial applications for materials deposition in a digital format call for a high degree of accuracy to satisfy the output requirements. Ink jet deposition has the potential to meet the requirements by delivering a consistent volume at a precise location in time and space. Currently available ink jet print heads employ multiple jets to enhance throughput and either the print head or the substrate is scanned relative to the other to complete the desired coverage. The timing and order of initiating jet channel firing is controlled by electronics and software, however, differences in flight time of the drops from the nozzle exit to the substrate can result in significant drop placement error. The difference in flight time is due to manufacturing tolerances that include channel-to-channel differences in print head geometry, materials, and drive electronics. A set of dimensionless parameters has been developed that describe drop placement error based on theoretical input as well as experimental data. Using a drop ejection visualization system, it is possible to measure drop flight time and other parameters that characterize the jetting behavior under realistic conditions. Theoretical calculations and experimental results for predicting the drop placement error due to the print head will be presented.

Introduction

Successful ink jet deposition for industrial, commercial and manufacturing applications relies on the precise temporal and spatial control of the deposition materials. Positioning mechanisms and ink jet print heads are engineered to provide the precise control needed. However, manufacturing tolerances and material inconsistencies can introduce considerable variability into the system. Drop placement error being the difference between the desired location and the actual location of the drop on the substrate is the manifestation of this variability. Drop placement errors are due to errors in positioning the print head and substrate relative to each other and errors in the drop ejection process.

Positional errors are most easily controlled by fixing the print head and moving the substrate in one, two or three dimensions. The alternative is to fix the substrate in one dimension, scan the print head in one or two dimensions and then advance the substrate after each scan. Either system is constructed using precision mechanical components regulated by electric motors with feedback control and high resolution encoders that supply the drop firing clock to the print head drive electronics. Although the design is by no means trivial, these types of mechanisms are well known and predictable.

Placement errors resulting from the drop ejection process are somewhat more complex than positional errors. When the drop firing clock pulse is received by the print head drive electronics, all needed drops are expected to eject and arrive at the substrate at exactly the same time. If the positioning mechanism has placed the substrate in exactly the right position to receive the drops, then the drop placement will be absolutely perfect. However, the reality of ink jet technology is that this is not the case. Differences in the print head system from channel-to-channel in the electronics, materials, geometry, and firing sequence can result in significant differences in directionality and flight time from the nozzle exit to the substrate surface.

Directionality errors may be the result of partial fluid clogs inside or outside the nozzle, an asymmetry in the nozzle shape, or wetting and filming of fluid at or near the nozzle exit. Any one or all of these conditions can cause the drop to be directed off the center of the flight axis. Flight time errors may also be caused by fluidic or mechanical crosstalk due to the close proximity of channels and the asynchronous nature of the data stream. A discussion of the mechanisms and causes of placement errors resulting from these conditions will be reserved for a future date. The focus of the paper will be on the analysis of placement errors due to differences in flight time for the drop ejection process during synchronous operation.

Drop Flight Time Error Analysis

As a drop begins to emerge from the nozzle exit in the ejection process, it undergoes a brief acceleration and then begins to decelerate. This deceleration continues as the drop progresses toward the substrate. Although this process is repeatable, it is difficult to measure the instantaneous drop velocity consistently and accurately from drop to drop in an array of nozzles on a given print head. The most important parameter to measure is the flight time of the drop from the nozzle exit to the substrate. Any drop-to-drop differences in flight time together with the perpendicular component of velocity introduced by the relative speed between the print head and the substrate will result in a drop placement error. If the deposition is interlaced in the scan direction in a bidirectional mode, the drop placement error will be twice that of the unidirectional mode. This analysis addresses the drop placement errors due to differences in drop flight time.

For drops fired simultaneously from two different nozzles that are equidistant from the substrate and are intended to land on the substrate simultaneously, the drop placement error between the two drops due to a difference in drop velocity may be written as

$$\mathbf{E = V_{HS}\, \Delta t_f}, \qquad (1)$$

where E is the relative drop placement error with respect to the ideal placement, V_{HS} is the relative velocity between the print head and the substrate assumed constant for this analysis, and Δt_f is the difference in flight time from the nozzle exit to the substrate of any two drops of differing velocity. If the flight time of the drops can be measured, then the difference in flight time can be written as

$$\Delta t_f = |t_2 - t_1| \,, \quad (2)$$

where t_1 and t_2 are the flight times of any two drops. If the distance from the nozzle exit to the substrate is assumed constant, an average drop velocity can be defined as

$$Vn = d_S / t_n \,, \quad (3)$$

where V_n is the average drop velocity, d_S is the distance from the nozzle exit to the substrate and t_n is the flight time for a given drop n. Combining equations (1), (2) and (3) yields

$$E = d_S V_{HS} |V_2 - V_1| / (V_1 V_2) \,. \quad (4)$$

Note that as the distance from the nozzle exit to the substrate increases, the relative print head to substrate velocity increases, or the difference in average velocity between two drops increases, the drop placement error also increases. In addition, as the average velocity of either or both of the drops increases, the drop placement error decreases.

A set of dimensionless parameters can be defined as

$$E^* = E/d_S \quad \text{and} \quad V_n^* = V_n / V_{HS} \,, \quad (5)$$

where E^* is a dimensionless error factor normalized by the distance to the substrate and V_n^* is a dimensionless average velocity normalized by the relative velocity between the print head and the substrate. Substitution of (5) into (4) yields a dimensionless error factor in terms of the dimensionless average velocities of two drops as

$$E^* = |V_2^* - V_1^*| / (V_1^* V_2^*). \quad (6)$$

For typical ranges of values such as

$$2 \le V_n \le 10 \quad \text{and} \quad 0.2 \le V_{HS} \le 2 \text{ [m/sec]},$$

$$0.5 \le d_S \le 2 \quad \text{and} \quad 0 \le E \le 0.5 \text{ [mm], then}$$

$$1 \le V_n^* \le 50 \quad \text{and} \quad 0 \le E^* \le 1.$$

Note that for an array of jets in a given print head, the maximum drop placement error will be related to the two drops with shortest and longest flight time or the maximum and minimum average drop velocities respectively. The drop placement error for all other drops will be less than that maximum. Although it is unlikely that the fastest and slowest drop will be adjacent on the substrate and thus less noticeable, this still represents the theoretical maximum drop placement error due to flight time differences.

Based on Equation (6), Figure 1 shows E^* as a function of V^*_{min} and V^*_{max}. It can be observed that when $V^*_{min} = V^*_{max}$, $E^* = 0$, however, note that when the value of V^*_{min} or V^*_{max} is small, a relatively small difference can result in a large error. Conversely, when V^*_{min} and V^*_{max} are large, large differences can result in relatively small errors. If V^*_{max} is held fixed and V^*_{min} is decreased, the dimensionless error increases rapidly. If V^*_{min} is held fixed and V^*_{max} is increased, E^* increases much less rapidly. Thus if V^*_{min} is maintained at a reasonable value, there can be a relatively large difference between V^*_{min} and V^*_{max} and the error can still be small. It is important to note that V^*_{min} and V^*_{max} decrease as the velocity between the print head and the substrate increases. Also note that the absolute error increases as the distance to the substrate increases. The equation for E^* and the graph in Figure 1 can be used to determine realistic expectations for drop placement error for typical values of constants and independent variables in the design process.

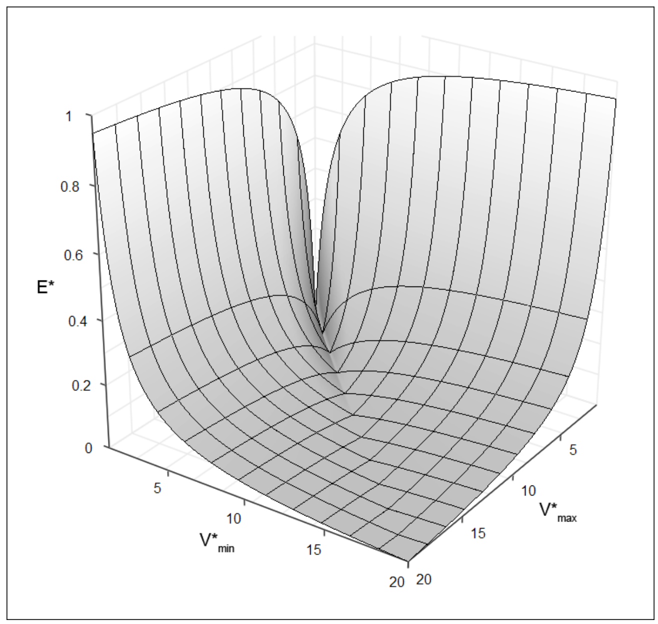

Figure 1 *Dimensionless Error as a function of V^*_{min} and V^*_{max}.*

Experimental System

To measure and analyze print head characteristics a drop vision system must be used. The Drop Watcher vision system available from *imaging Technology international, Corp.* is an out of the box system for analyzing a wide range of print heads currently available. The Drop Watcher provides a measurement system for researchers and engineers who need information on jet'able fluids and print head performance and properties.

Figure 2 shows an *iTi* Model III automated Drop Watcher with a *Dimatix* Spectra SE-128 print head mounted in the observation area. The Drop Watcher allows comprehensive and rapid analysis of ink jet drop generation including motion, uniformity, formation, flight time, merging time and distance, relative drop volume, velocity and jet straightness. Data is easy to access and control with a graphical user interface as shown in Figure 3. The system provides reporting and storage of complex data in a Microsoft Excel spreadsheet.

Figure 2 *iTi Drop Watcher III*

Because the Drop Watcher uses a variable magnification lens we are able to vary the theoretical substrate distance. The software provides for tracking drops from ejection at the nozzle throughout flight and allows users to measure ink jet drop parameters at any point of flight.

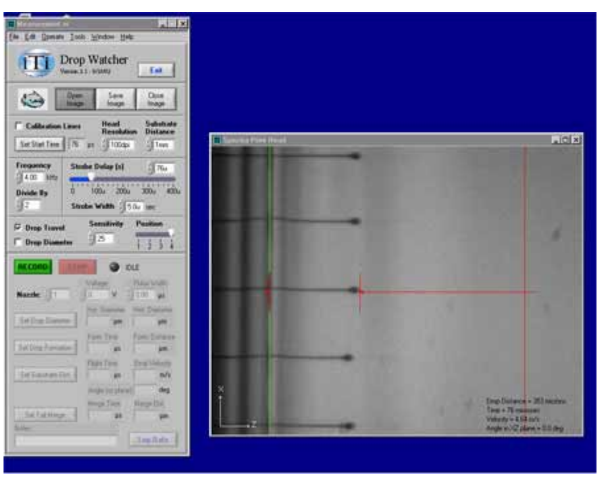

Figure 3 *Drop Watcher User Interface and Analysis Window*

Our experimental setup included a Drop Watcher III and three *Dimatix* Spectra print heads. The print heads were the Spectra Nova, Spectra SE-128, and Spectra SX3 (Prototype). These print heads are currently used in a wide range of graphical and materials deposition systems today. The SX3 (P) was operated in the "untrimmed mode" for this testing. *Dimatix* offers a trimming option that allows the user to match the flight time on a nozzle by nozzle basis in order to greatly reduce or eliminate flight time error. All tests and analysis were accomplished using a certified model fluid in each print head for accurate drop ejection.

Experimental Results

The iTi Drop Watcher discussed in the previous section was used to evaluate three *Dimatix* Spectra print heads. Figure 4 shows a typical graph of instantaneous drop velocity as a function of distance to the substrate averaged over several channels of a multi- nozzle print head. The graph clearly shows the difficulty of measuring instantaneous drop velocity as discussed in the analysis section above.

Figure 5 shows the values for Flight Time, Drop Formation Time, Tail Merge Time and Drop Volume for each of the 128 channels in the print head. Although the measurements were taken for a fixed value of drop frequency, drive voltage and pulse width, the data is typical for print head operation at less that 10 to 12 kHz. Using this data, the mean, standard deviation and range for each parameter can be calculated.

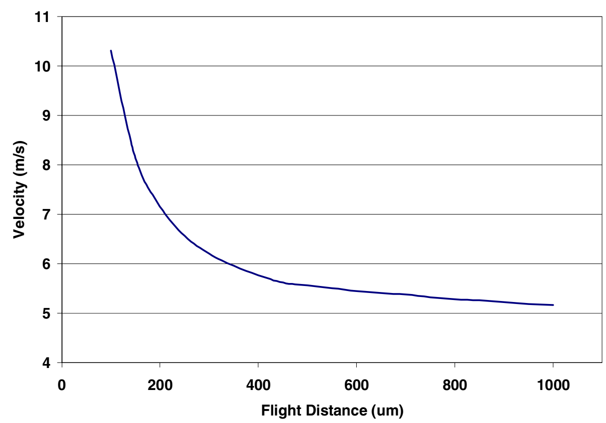

Figure 4 *Drop Velocity as a function of Flight Distance to the Substrate*

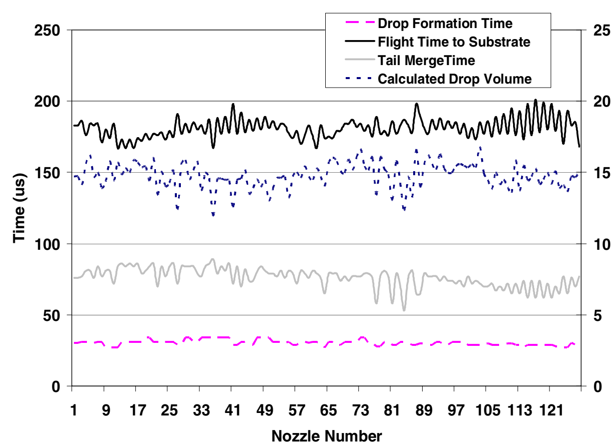

Figure 5 *Dimatix Spectra SX3 (Prototype) Print Head Performance Data*

Figure 6 shows the maximum predicted drop placement error based on the range of flight times measured for three *Dimatix* Spectra print heads. For graphics applications at low resolutions, a drop placement error of as much as 50 µm may be acceptable. However, digital fabrication applications may require errors to be less than 5 µm.

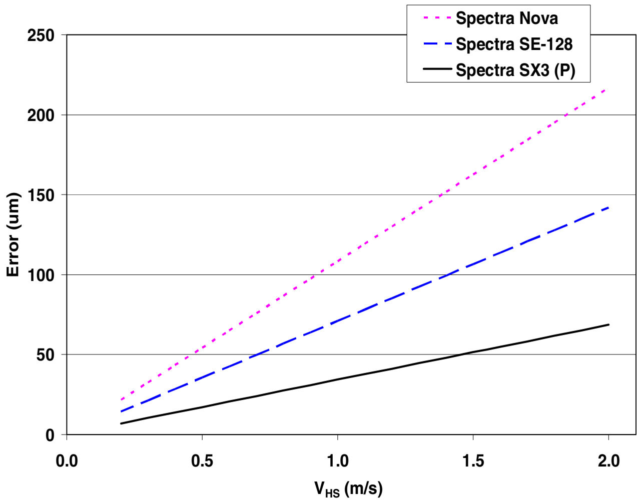

Figure 6 *Absolute Error vs. Relative Print Head / Substrate Velocity at Substrate Distance of 1mm*

The Nova print head delivers a nominal 80 picoliter drop volume for relatively low resolution applications. The predicted drop placement error for print head to substrate speeds of up to 0.45 m/sec would be less than 50 µm. The SX3 prototype print head with a nominal drop volume of 12 picoliter could run up to 3 times as fast for the same drop placement error or could run at the same speed with about one fifth the error. Note that the data reported here is for a particular value of frequency, drive voltage, pulse width, and rise / fall time and no attempt has been made to optimize these parameters in order to minimize flight time errors. Optimization would provide a significant improvement but would not completely eliminate flight time errors. Applying the trimming option to the SX3 (P) would virtually eliminate the flight time error in the synchronous mode of operation.

Conclusion

Precise placement of deposition materials has become a major factor in the success of ink jet technology in the industrial and commercial marketplace. From the above it is possible to determine the theoretical error that will be inherent in any ink jet application due to the flight time differences in a print head. We have shown how differences in flight time will affect drop placement and how to minimize drop placement error. Using the given examples and formulas the necessary printing parameters can be found to keep the error within an appropriate constraint.

While it is impossible to eliminate all error due to the nature of imperfections in materials and manufacturing, it is possible to minimize the error by careful selection of the printing parameters used and by verification of the printing characteristics of a given printing mechanism.

Acknowledgement

The authors would like to express their appreciation to Mr. Jared Herring for his work acquiring the necessary data for this paper.

Biography

Dr. Mills founded iTi Corporation in 1992 as an ink jet consultancy and developer of ink jet prototype print heads including iTi's proprietary ESIJET™ technology. Since that time, he has helped position the company as a leading ink jet integrator. Prior to founding iTi, he worked for IBM and Lexmark as a Researcher, Senior Engineer and Product Manager from 1978 to 1991. Dr. Mills received his PhD and MS in Engineering Science from the University of California Berkeley and BS Degree in Aerospace Engineering from the University of Texas at Austin.