MICRO-POSITIONING FOR PRECISE INK JET DELIVERY

Anthony W. Gatica
M3 Design Inc.
Round Rock, TX, 78681

BACKGROUND

Ink jet delivery systems are integral to many fields, such as paper printing, display creation, and three-dimensional rapid prototyping applications. Printheads are able to dispense picoliter-sized fluid droplets thousands of times per second. Furthermore, the printheads' versatility enables the dispensation of inks, solvents, suspended particles, or biological material. Examples are in the fields of electronics, display technology, and life sciences [1]. By mounting an ink jet delivery system to a moving carriage and passing it over a substrate, fluids can be deposited at precise locations.

Additionally, ink jet printing is an additive process, enabling production processes at the micron level with minimal waste. This can result in low cost and highly accurate products, especially at low volume manufacturing.

While the dispensing precision of the printhead is typically very good, the mechanical tolerances associated with head location are much larger and complex, thus requiring additional setup and adaptive control in order to obtain the most accurate system. Such adjustments are made via a combination of shifting the print heads and varying the print timing.

This paper will investigate methods that can be used to obtain an accurate system of print heads through mechanical adjustment, calibration, and software/hardware control. A successful machine architecture will strike a thoughtful balance among these three categories of compensation. A conceptual embodiment of such a printing system will also be presented and discussed.

CHALLENGES

In a multiple printhead system, there are multiple errors to consider that affect positional accuracy:

- Head-to-head location variability
- Distance from individual printhead to the printing substrate (head gap)
- Individual printhead non-parallelism to the substrate
- Head-to-head nozzle pitch variations
- Exiting drop velocity and trajectory: Nominal variance plus transient effects due to ink temperature
- Orthogonal error of the substrate after loading, relative to the printhead array
- Substrate rotation relative to printhead array as a function of substrate linear position.
- Printhead array rotation relative to substrate as a function of array linear position

Many of these errors can be compensated with mechanical adjustments, calibration, and software control.

MECHANICAL ADJUSTMENTS

The primary method to compensate for non-accurate printhead alignment is to simply adjust the heads in six degrees of freedom. However only three degrees of freedom are necessary: X, Z, and θ_Z as shown in Figure 1. Adjustment X controls head-to-head spacing, Z controls the distance from the printhead to the substrate, and θ_Z controls the apparent nozzle pitch. The Y-axis coincides with the system motion over a substrate to deposit ink, and can be compensated for by pre- and post-firing timing changes per nozzle. Nozzle bow can also be compensated for in this manner. Rotations about the X- and Y-axes can typically be minimized through proper design and datum control principles in a cost-effective manner such that no compensation is required.

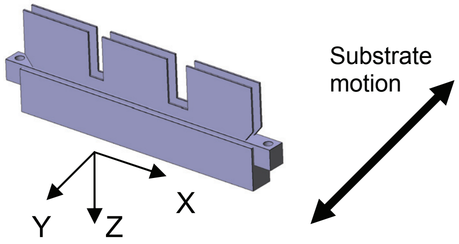

FIGURE 1. Print head coordinate system and axes relative to substrate motion.

Implementation of the adjustments can vary from flexures to mechanical bearings. Friction and hysteresis are the biggest sources of positioning errors. Feedback control must be utilized.

Continuous Print Coverage

No matter how close print heads get to one another there will always be a gap in printed material between adjacent heads. In order to get continuous print coverage, rows of print heads can be offset in the Y-axis to provide mechanical clearance for the printhead size and fine-tuned in the X-axis, as shown in Figure 2, such that the array of print nozzles appears to be continuous.

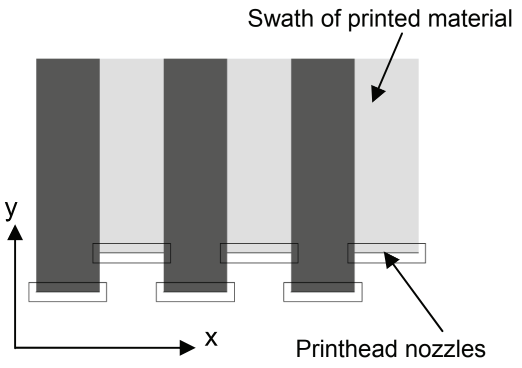

FIGURE 2. Staggering six printheads to get continuous print coverage.

Compensation for Rotation Errors

The source of rotation errors between the substrate and the printhead array may be either θ_z in the X or Y motion stage axes or simply the substrate was not loaded accurately. Three compensation approaches are valid:

- Rotate each head individually and translate as needed.
- Rotate the printhead array as a unit.
- Rotate the substrate precisely at load and during stage motion.

The implementation shown later in this paper utilizes the second approach.

Adjusting Nozzle Pitch

Although the printhead nozzle pitch is fixed, the head can be rotated in θ_Z to reduce the apparent pitch (Figure 3). The apparent pitch is calculated as $P^*\cos\theta_Z$. This allows for denser print coverage or controlling spacing of ink drops. When the printhead rows are rotated to shorten the apparent nozzle pitch, each row needs to translate to maintain a contiguous array of nozzles (Figure 4). Fine adjustment of the print heads is accomplished by the individual X-adjustment and θ_Z adjustment as shown in the print head coordinate system (Figure 1). Sub-micron adjustment can be achieved reliably with miniature motor/gearhead actuators or piezo-electric actuators, coupled to stiction-free bearing assemblies or flexure element bearings.

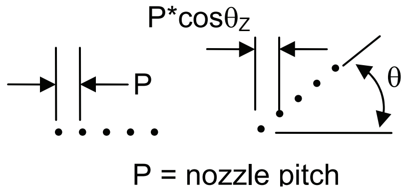

FIGURE 3. Reduction of apparent nozzle pitch by rotating print heads.

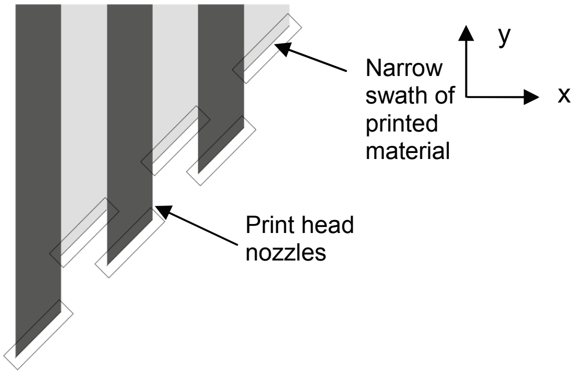

FIGURE 4. Rotating a group of print heads in θ_Z to reduce the apparent nozzle pitch. Note the print head rows have translated relative to one another to obtain continuous print coverage.

SOFTWARE ADJUSTMENTS

Certain print head designs have individually-addressable nozzles. This allows variable timing of each nozzle and can be put to use as described in the next sections. An example of such a print head is the Dimatix Spectra® SX3 with 128 addressable nozzles [2].

TABLE 1. Partial list of Sprectra® SX3 specifications [2].

Specification	*Value*	*Units*
Drop Size	*12*	*Picoliters*
Drop Velocity	*8*	*meters/s*
Drop Velocity Variation	*<2*	*%*
Max Operating Frequency	*10*	*kHz*

Print Head Gap & Parallelism Compensation

Precision ink jet printheads are used in many applications that require extremely small gaps between the print head and substrate. As the gap decreases, the parallelism between the print head and the substrate becomes more sensitive. If the printhead is moved relative to the substrate in the Y-direction (Figure 1) and all nozzles were fired at the same time, the ink drops would strike the substrate at different locations if the head was not parallel to the substrate. Figure 5 presents the equations of motion for a falling ink drop at an initial exit velocity.

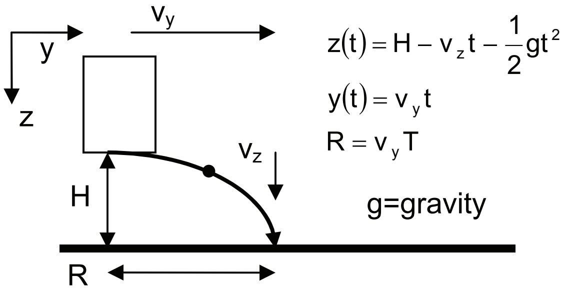

FIGURE 5. Equations of motion governing drop placement during jetting and print head velocity relative to a fixed substrate.

In Figure 5, the value H is the nominal distance between the print head and substrate and T is the nominal time for a drop to strike the substrate after ejected from the print head based on the drop exit velocity and distance H. As an example, let H=0.001m, v_y=1m/s, v_z=8m/s. Setting z(t)=0 and solving the resulting quadratic equation for t, t_1=0.00012499s and t_2= -1.6311137s. Obviously t_1 is the only realistic answer. The resulting distance the drop travels in the y-direction to the substrate is R=0.00012499s * 1m/s = 0.00012499 m or 124.99 microns.

In a multi-printhead system, the necessity to set the working gap of all printheads very close is essential. From the example above a 1% error in nominal working gap between two printheads would result in a 1.25 micron landing error when printing uni-directional. This would double when using bi-directional printing.

If the parallelism of the printhead to the substrate varies by 25 microns from the first nozzle to the last, H=.001025m at the last nozzle. Assuming the other parameters remain the same, the new time to strike the substrate equals 0.00012811s. The resulting value for R is 0.00012811m or 128.11 microns. Thus, a 25 micron parallelism error results in a 3 micron error in drop placement at a relative velocity difference of 1 m/sec.

After the parallelism error is measured or calculated, the timing of firing each nozzle can be adjusted. In the above example, in order to compensate for the parallelism error, the timing on the last nozzle would be advanced so it fired before the first nozzle. If the first nozzle required 0.00012499s for an ejected drop to strike the substrate and the last nozzle required 0.00012811s, the last nozzle should be fired 0.00000312s or 3.12 microseconds sooner.

Adjusting Ink Coverage

For applications that require depositing ink or other material, the amount of material deposited from a given printhead can be controlled in the following manner:

- Vary velocity of print heads relative to the substrate (higher velocity reduces the material dispensed per unit area)
- Vary head jetting frequency (high frequency yields more material dispensed)
- Vary drop spacing by reducing the apparent nozzle pitch (closer spacing of printed drops yields more dispensed material per unit area)
- Vary drop spacing by reducing the number of active jetting nozzles (reduces the dispensed material per unit area)
- Substitute a different printhead to increase or decrease the individual drop volume

Print Head Jetting Calibration

One method to determine the non-parallelism between printhead and substrate is to utilize an optical inspection system to capture images of the ink drops as they exit the print head. Other benefits of the optical system are the ability to measure the exiting drops' trajectory relative to the printhead, and measuring actual drop velocity and volume.

Calculating Parallelism Errors

The optical inspection system can scan along the edge of the print head, monitoring the print head position in the field of view. Thus, the parallelism of the print head relative to the head inspection camera scanning axis can be calculated.

Measuring Ink Drop Velocity

A method to determine ink drop velocity is to strobe a machine vision system multiple times after the ink drop has been ejected from the print head and measure the distance between the drops (assuming the camera's region of interest scale has been calibrated). Figure 6 outlines this graphically.

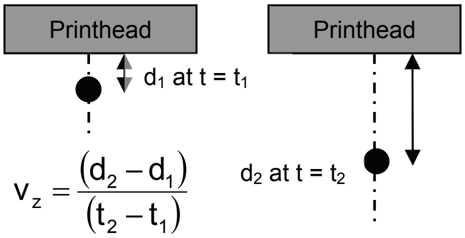

FIGURE 6. Method to calculate ink drop velocity using machine vision.

Ideally t_1 and t_2 would be selected so that the positional midpoint between ink drops represents the chosen working gap for the printhead array.

CONCEPTUAL IMPLEMENTATION

A conceptual implementation of the print head array is shown in Figure 7. This conceptual design has the following features:

- Machined disk containing all print heads
- Air bearing axial support of the disk
- Air bearing radial support of the disk
- Non-contact brushless motor to adjust disk angle
- Groups of printheads ganged together with linear movement of each group
- Individual print head adjustment (3 degrees of freedom) for fine head adjustment

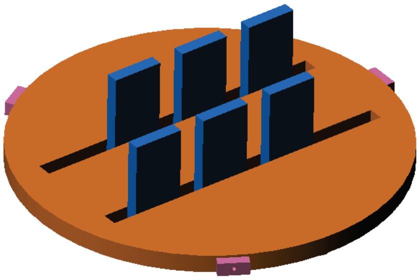

FIGURE 7. Conceptual embodiment of an adjustable print head assembly.

Figure 8 presents how the print heads translate in order to print continuous swaths of material during the disk rotation. As the number of rows of print heads and the number of print heads in each row increase, the disk must become larger. Self deflection of the disk and manufacturing limitations will dictate the maximum size and number of print heads allowable.

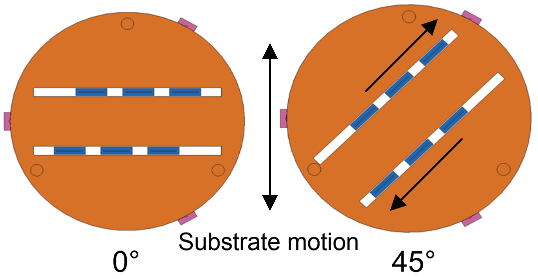

FIGURE 8. Translation of print heads needed to print continuous swaths of material as the disk rotates.

SUMMARY

Ink jet dispensing of inert, organic, or biological materials opens up a wide range of potential applications. Examples are in the fields of electronics, display technology, and life sciences [1]. Furthermore, ink jet is an additive process that doesn't require intermediate masking steps such as photolithography and efficiently uses material without waste.

Commercially available printheads can dispense a wide range of materials with incredible precision. However, assembling them into a usable product requires precise adjustment, calibration, and software control.

Methods that can be utilized to create and calibrate such a printing system have been presented. Additionally a conceptual embodiment of this system has been presented.

REFERENCES

[1] Schloeppler M. New Approaches for Materials Deposition [article on the Internet]. Productronica; 2005, Nov. 17; Munich, Germany; Available from: http://www.dimatix.com/files/productronica_11172005.pdf.

[2] Spectra® SX3 128-Channel Jetting Assembly. [web page on the Internet]. California: FUJIFILM Dimatix, Inc.; 2007, Apr. 05. Available from: http://www.dimatix.com/files/PDS00053_SX3.pdf.