Positional Accuracy for Ink Jet Deposition in Digital Fabrication

Ross N. Mills; imaging Technology international (iTi) Corporation; Boulder, Colorado, USA and Graham Vlcek; In Position Technology; Golden, Colorado, USA

Abstract

Components or systems that rely on ink jet deposition of complex materials for functional reliability may require a very high level of drop placement accuracy. Drop placement accuracy is a function of print head jetting properties and the mechanism controlling the print head position relative to the substrate in both a spatial and temporal sense. This paper will focus on the control and minimization of positional errors to afford the best opportunity for minimal drop placement error from a given print head. Ink jet deposition is a static and dynamic process that depends on mechanical tolerances, changes in position during motion, and predicting position prior to the actual event of drop ejection. Traditional methods for error assessment use positional accuracy and repeatability as the primary measure. The emphasis for this paper will be on the motion control and mechanical error sources that affect these parameters. Methods for measuring and techniques for reducing error along with examples will be presented.

Introduction

The use of ink jet deposition in digital fabrication and integration into manufacturing processes continues to generate high levels of interest among scientists and engineers [1]. The key for success in ink jet deposition relies on the ability of the system to place droplets of material at a precise location in time and space. Ink jet print heads and positioning mechanisms provide the vehicles for accurate drop placement. Drop placement accuracy is a function of print head jetting properties and the mechanism controlling the print head position relative to the substrate. The effect of print head jetting properties has been discussed previously [2].

Ink jet deposition is a static and dynamic process that depends on mechanical tolerances, changes in position during motion, and predicting position prior to the actual event of drop ejection. Traditional methods for error assessment use positional accuracy and repeatability as the primary measure. The emphasis for this paper will be on the motion control and mechanical error sources that affect these parameters for a typical XY planar deposition system.

Positional Errors

Positional errors in a motion control system are often defined in terms of accuracy and repeatability. When deposition or printing is done on a planar or XY surface, the positional accuracy determines the overall size of the image and the location of various features within the image. If only one material is being deposited on a substrate with no preexisting features, then the relative size of the image compared to the intended size may not be important. However, if there are features or subsequent layers by other processes, then positional accuracy is very important. If the previous or subsequent layers are to be deposited by the same ink jet mechanism, then positional repeatability becomes very important. Although the definitions depend somewhat on the mechanical configuration, the errors and hence the accuracy can be defined in the context of the XYZ linear stages used to transport substrates and print head used in ink jet deposition.

Positional Accuracy – Accuracy of a motion control system is specified as a measurement of the system's ability to position its payload (print head or substrate) relative to all other points within its travel. System errors are often described by their linear components often referred to as straightness, flatness and lead errors, which create a three-dimensional value for accuracy at a given point in the travel. Although measurements are taken as three-dimensional values, they are actually affected by movement of the system in six dimensions which are X, Y, Z, Roll, Pitch, and Yaw. Where X is the scanning direction for deposition, Y is the step direction for incrementing between deposition scans and Z is the axis from the surface or plane of the substrate to the ink jet nozzle as shown in Figure 1. Roll, Pitch and Yaw are the rotational coordinates around the X, Y, and Z axes respectively.

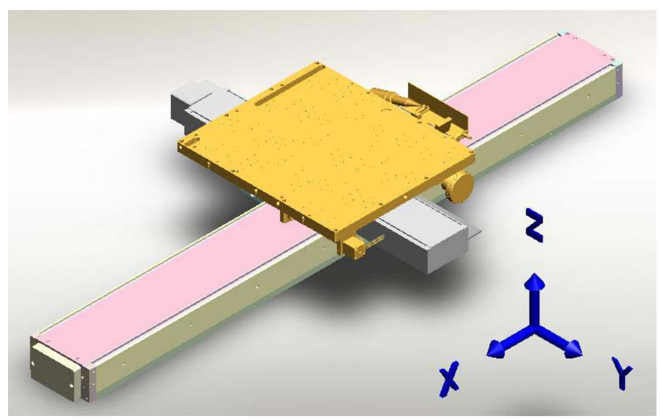

Figure 1 *Typical transport mechanism for a stationary print head and moving platen.*

Rotational movements affect payload errors proportionally to its distance from the center of rotation. Errors created by rotation have components in two-dimensions and have varying contributions depending on system configuration thus making adjustment or compensation very difficult.

Positional Repeatability – Repeatability of motion control systems is specified as the system's ability to return its payload to the same position each time it's commanded to do so. Repeatability errors are functions of clearance, preload, or mechanical hysteresis and are often 2 to 20 times better than accuracy measurements for the same system.

Error Sources – Positional errors of a motion control systems can be broken into electrical and mechanical contributions. In linear or rotary motor stages, most electrical contributions to error are associated with the forcer/feedback system and are mostly seen as lead errors. Mechanical components contribute to error in all six dimensions and are commonly functions of base material, base tolerances, bearing type, bearing quality, and payload mounting.

An additional source of accuracy error occurs in multiple axis stack systems due to deviations from perpendicular mounting. As the axes are mounted together, the offset from perfectly perpendicular is referred to as the orthogonality error, often in the range of 5-30 arc-sec for precision stages. This offset will create a positional error parallel to the X-axis as the payload is moved in the Y-direction.

System Components

Figure 1 shows the transport mechanism for a typical ink jet deposition system in which the print heads would be mounted above the platen jetting down onto the substrate. The print heads are held stationary while the substrate mounted to the platen is scanned along the X-axis and stepped in the Y-axis in between X moves using linear motors. The Z distance between the substrate and the print head is a constant nominal value of 1 mm. A second ink jet deposition system is shown in Figure 3. In this system, the print head is scanned in the X-axis using a linear motor attached to a moving gantry that is stepped in Y using a servo motor-ball screw arrangement on each end of the gantry.

Figure 2 *iTi VJet with scanning ink jet print heads and duel stage stepping gantry for rigid substrates up to 1.2 m by 0.9 m of printable area.*

Stage construction for high precision axes has become somewhat similar between various suppliers. A cross section of typical stage construction, as shown in Figure 3, begins with a base machined to tight tolerances, to mount the rails and magnets. The most common base material is aluminum due to its strength, lightweight and ease of machining. Any inconsistencies in the base construction will appear in several of the measured errors, as they tend to have both a directional and rotational contribution to payload offsets. Bearing races are often tested and honed by hand with an oilstone to remove any high points and ensure flatness. Once the base is ready, precision ground and matched bearing rails are mounted to the stage base material using a reference edge to

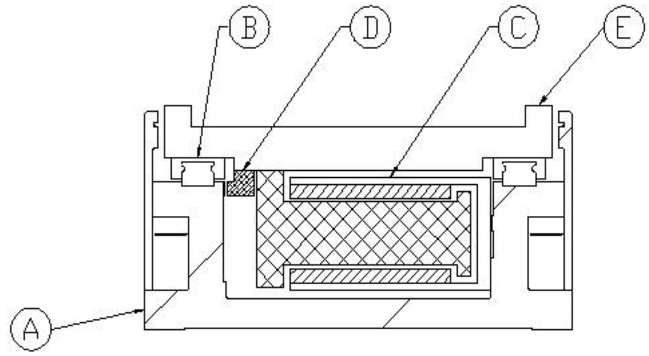

Figure 3 *Typical linear motor cross section showing A: base, B: bearing rail and block, C: linear motor and magnet, D: Linear encoder and scale, E: carrier for payload.*

align one or both of the rails to ensure they're straight. Bearing rails are separated by grades where the highest quality bearings have the best accuracies and matched sets are often coupled on the same actuator for the best results. Recirculating ball bearings, also matched, are mounted to the carriage and added to the stage. In systems requiring the highest accuracy, air bearings can be used to replace the mechanical bearings in "cost is no object" systems. These bearing allow the use of granite or other flat bearing surfaces where high tolerances are attainable and the bearing is able to 'float' over imperfections.

Ball screws and linear motors dominate the forcer technology on precision stages. Ball screws allow for higher forces and a stiffer system due to the linear gearing and high preloads. Ball screws are either ground or rolled to shape. Ground screws are generally higher accuracy because the machine is constantly compensating for errors, but with higher prices. Rolled screws tend to have less accuracy but exhibit a more linear error curve (constant lead error) making compensating for error easier. Ball screw nuts contain recirculating balls to transfer the rotation of the ball screw to linear motion efficiently. Preloaded ball nuts use either oversized balls or two spring-coupled nuts that create a centering force to reduce system backlash. Ball screw assemblies can be driven by a conventional integrated or coupled servo or stepper motors.

Linear motors have improved dynamic characteristics but limited forces and lower duty cycles. Linear motors are capable of accelerations of several Gs, and are directly coupled to the load, eliminating backlash. A linear motor is a servomotor flattened out and operates on the same principles as a rotary motor. The three types of linear motors are iron-core, ironless, and a hybrid of the two. Iron-core motors use a single row of magnets and an iron plate on the backside of the motor coils to complete the magnetic circuit. Ironless motors place the coils between two rows of opposing magnets. Iron-core motors are capable of higher peak and continuous forces but require larger bearings because the attraction force between the motor and magnets is 2-3 times the thrust force generated depending on the motor-magnet gap. This force can be great enough to create motion based payload errors as the material's spring coefficient becomes part of the equation. Ironless motors have better force to weight ratios for improved dynamics but a lower continuous to peak force ratio. These motors only produce thrust forces in the direction of travel. The higher dynamic capabilities and lack of additional forces have made ironless motors the primary choice for deposition machines.

Regardless of the transport technology used, a feedback source is required for any closed-loop servo system. To maximize the accuracy of a system, it is advisable to position the encoder as close to the payload as possible to reduce coupling errors. In both the systems shown, optical linear encoders are used where a linear tape or glass scale is affixed to the base material and a read head is attached to the load plate. The scale has lines precisely placed at constant intervals of 2, 4 or 20 um depending on scale resolution. The encoder head has optics equally spaced and reads the amount of light returning from the scale as the head moves along the scale. The resulting signal is a sine wave that is often converted to a TTL-level signal in quadrature, either internally or externally, into various resolutions to be fed into the controller. Ball screw systems can operate with a rotary encoder affixed to the rotary motor. This configuration is the standard for medium precision applications but relies on the ball screw's accuracy in addition to other components. Given a linear encoder's accuracy is significantly better, they are the preferred feedback source. When a linear encoder is used, the accuracy of the ball screw is removed from the equation and the system accuracy becomes a function of the base, bearings, encoder, and application of the axis.

All of the components come together to create a linear axis in a motion control system. The motion control system is then integrated with the print head drive, data and support system to complete the digital deposition system. Depending on the application, requirements, environment, and of course budget, different technologies and constructions are preferable.

Error Measurements

The method used by stage manufacturers to determine the accuracy and repeatability of their products is fairly standard throughout industry. The process involves testing the axis using a laser interferometer, which returns a 3-dimensional position in space with nanometer accuracies. A single axis is mounted to a precision, vibration isolated granite slab, located in climate-controlled room. An optic is placed in the center of the carriage at a specified height (often 1-3") above the mounting surface. The stage is exercised through its range of travel while the controller specified stage position is compared with the actual position as measured by the interferometer. The resulting difference is the error, or accuracy of the stage. The perpendicular deviations in travel by the optic in the Y and Z directions are measured as the straightness and flatness. To determine the repeatability of the stage, it is returned to various positions several times within the travel range and the difference in position between each cycle is the repeatability.

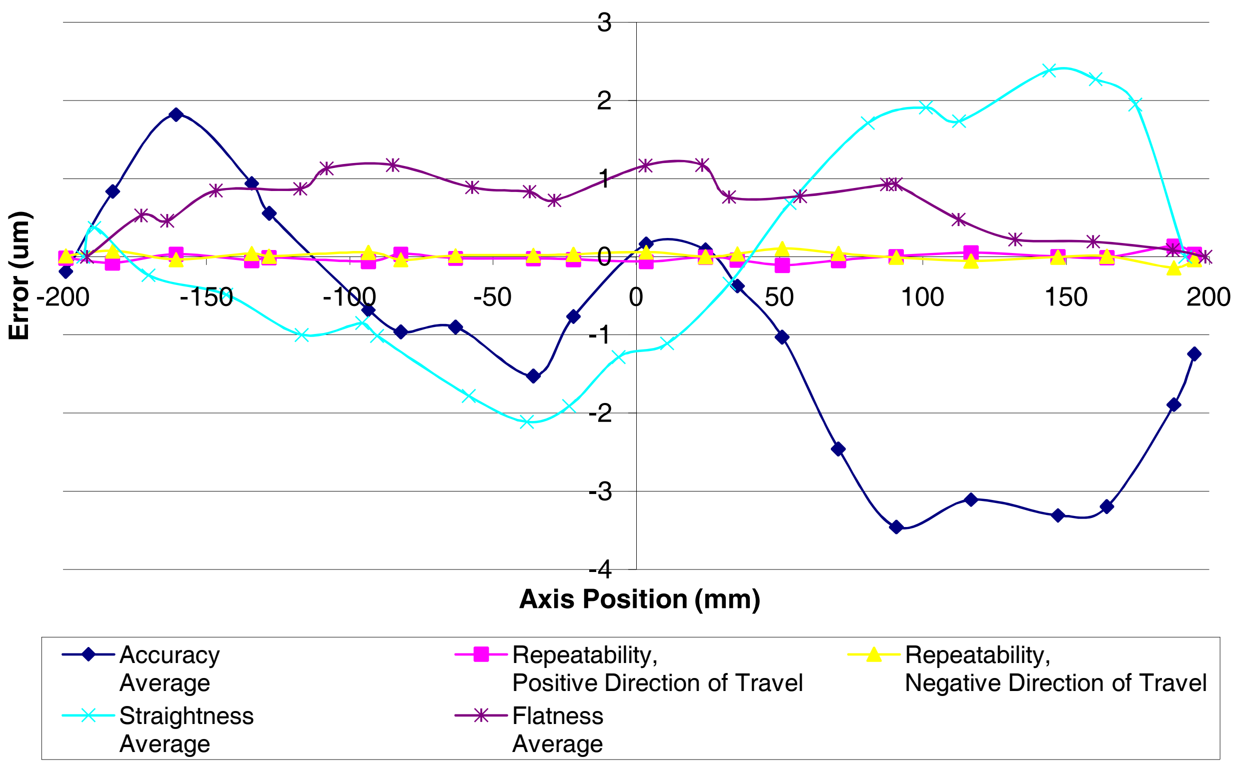

Figure 4 *Typical error plots for accuracy, repeatability, straightness and flatness as a function of position along the motion axis of the stage.*

Figure 4 shows a set of typical error plots for accuracy, repeatability, straightness and flatness over 400 mm of stage travel as a function of position along the axis of travel. As can be observed, the average accuracy varies from +2 to –3.5 µm over the entire travel and the repeatability is in the sub 100 nm range. The straightness ranges from –2 to +2.5 µm and flatness from 0 to 1.2 µm. In order to resolve straightness and flatness into actual errors, knowledge of the geometric configuration is required. Determining the center of rotation with respect to the substrate and or each individual nozzle is also necessary to determine the roll, pitch and yaw contribution to overall error.

Conclusion

In addition to precise motion control, other techniques such substrate alignment tools can also be used to better align the substrate or previously printed structures with the motion axes to reduce error [3]. However, in any given motion control system, the overall system accuracy is a sum of its parts where each component has its own contribution to system accuracy and repeatability errors. Proper selection of technologies, components, processes and integration of those will always be the best path to success for deposition machines and processes. In addition, precision machining techniques continue to make better parts at lower costs bringing precision motion components to market that are better and more affordable. As heads, inks, and jetting technologies improve, accurate drop placement continues increase in importance.

The latest generation deposition heads and technology have necessitated more accurate machines than the sum of their parts can produce. Therefore, the next progression for companies making the most accurate deposition machines will be to utilize the smaller repeatability values and turn them into accuracy by mapping errors and feeding them into the control system as offsets. The technique will also allow machine builders and users to determine accuracy and repeatability numbers for the system as a whole where the currently multiple axis stacks aren't tested. This will allow 'mapped' axes with resolutions in the 10 nm range to perform with repeatability in the 10's of nm range and accuracies in the 100's of nm range.

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Dr. Ross N. 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 1992. Dr. Mills received his PhD and MS in Engineering Science from the University of California Berkeley and BS Degree in Aerospace Engineering with Honors from the University of Texas at Austin.

Graham Vlcek is the applications engineering and value-add manager for In-Position Technologies, a leading distributor of precision motion control components. He received his BS in Engineering with a major in both Electrical and Mechanical Engineering from Colorado School of Mines.