# Substrate Alignment for Single and Multilayer Ink Jet Materials Deposition in Digital Fabrication Systems

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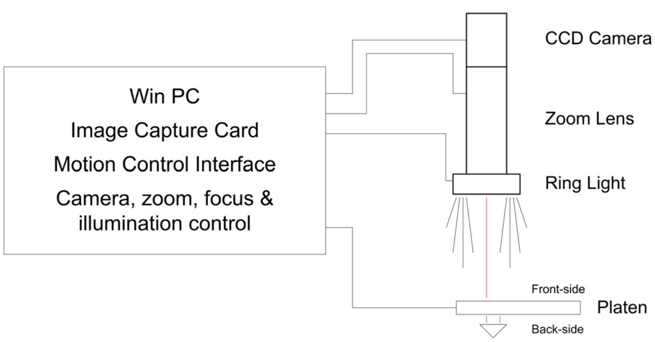
## Abstract

*As materials deposition technologies for digital fabrication evolve, the inevitable push toward volume manufacturing will necessitate the application of alignment and inspection technologies to monitor and control the production process. Many of these processes will depend on ink jet deposition of materials onto substrates with previously or subsequently applied structures or images. The successful function of the end product will depend on the precise alignment of materials from layer to layer. This paper describes the development of a Substrate Alignment Tool (SAT) using machine vision methodologies for rapid in-line measurement and adjustment of the alignment between layers. In addition, the SAT can double as an Image Analysis Tool (IAT) for* in situ *monitoring of process quality. This paper will focus on the design and use of the SAT for ink jet applications. Of particular concern to this study will be the identification of error sources and their contribution to process accuracy and repeatability.*

## Introduction

Successful ink jet deposition for industrial, commercial and manufacturing applications relies on the precise temporal and spatial control of the deposition materials[1]. It is unlikely that all processes and products will be fabricated by a single technology. However ink jet is likely to be a major contributor in the field of digital fabrication[2]. For any multilayer system, ink jet will contribute to one or more of those layers. Positioning of an image in a precise location in preparation for subsequent images or an overlay for previously deposited images relies not only on the positional accuracy of the system but also on the precise positioning of the substrate prior to starting any deposition process. Such a system is introduced here as the Substrate Alignment Tool (SAT).




SAT System Diagram

The SAT system consists of an optical and image capture system for viewing; an X, Y, and Θ motion system for positioning; a platen that holds the substrate in place during processing and allows for dimensional calibration; and a software control system that aids and guides the user through the alignment process.

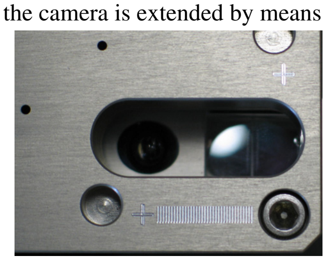
## Optical and Image Capture System

The camera and lens assembly is shown in the photo and consists of a CCD camera, microscope zoom lens with motorized zoom and focus adjustment, and a LED ring illuminator for viewing the substrate. Camera video is attached to an image capture card that resides in a personal computer running a Windows® environment.

Control of the various camera functions are accomplished with a small box external to the printing system referred to as the Pendant. The Pendant includes controls for the motorized zoom and focus as well as ring light and back-side illumination. In this way, user controls are grouped and in a convenient location, mechanically decoupled from the deposition system, and clear of safety interlocks.

The remaining optical system components comprise the back-side viewer. The platen incorporates two illuminator-prism assemblies and appropriately located slots for viewing the back of the substrate. The focal length of the camera is extended by means of adding an objective lens to the assembly, thereby allowing the system to focus on the back side of the substrate.

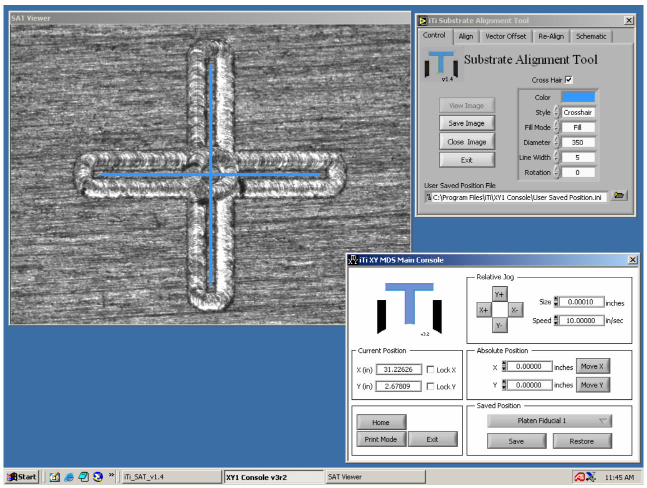

Pendant



Back-Side Viewer

## Motion Control System Interaction

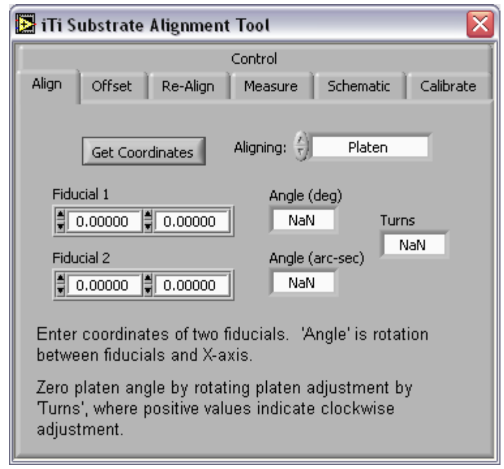
In the iTi XY Materials Deposition System, the substrate is held by vacuum to a platen that is scanned in X and incremented in Y beneath a fixed print head. The SAT camera is similarly fixed and as such is subject to motion system repeatability and accuracy. For this reason, the SAT acts as a supplementary system, facilitating the location and measurement of image features and nozzle location.


XY-MDS and SAT Applications

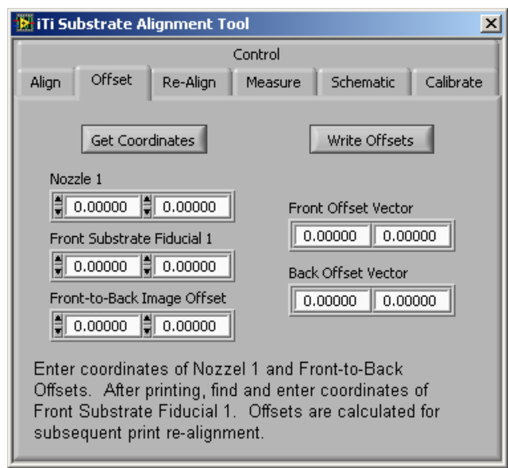
## SAT Viewer Application

Several interactions and mathematical manipulations of motion coordinates are required to facilitate substrate alignment. The SAT Viewer application provides a convenient means to facilitate said interactions and manage intermediate results. A short introduction to each of the tools follows.

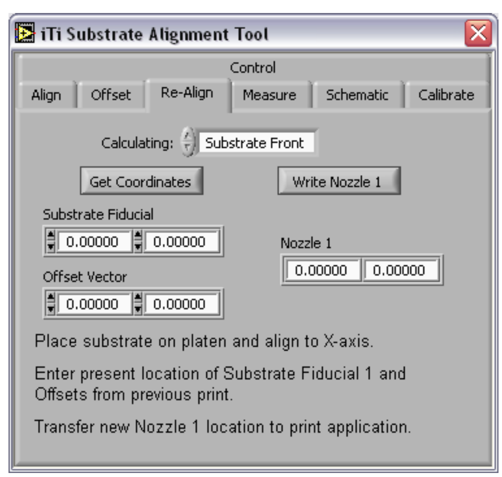

The Control tab is displayed at program launch or when the user manually selects it via the tab control, located in the top of the program window. Virtual Target controls are located on the right of the tab, enabling the user to customize the alignment target to suit a particular substrate fiducial.



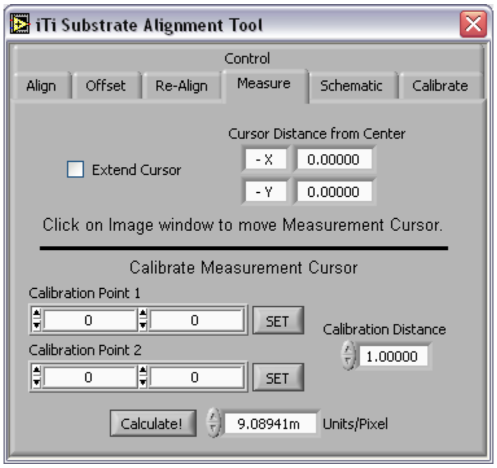

The Align tab is used to determine the angle between the X-axis and a pair of fiducials, with results reported in degrees, arc-seconds and the number of turns of the platen rotational adjustment required to zero the angle.



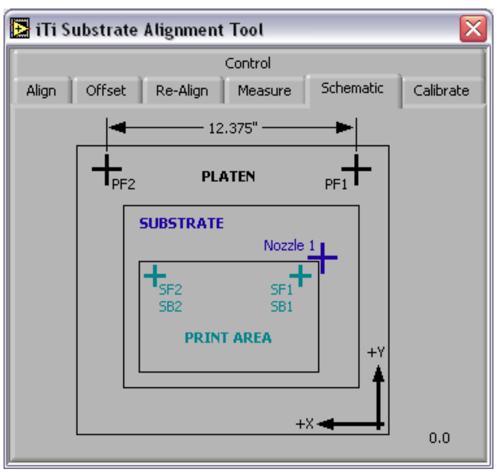

The Offset tab is used to determine offset vectors for later use in calculating a corrected Nozzle 1 location; for example, when re-aligning the substrate for further printing.




The Re-Align tab is used to calculate the Nozzle 1 (print) location when printing second and subsequent passes on a particular substrate. The calculated Nozzle 1 coordinates represent the location from which printing is perfectly aligned with the previous print.




The Measure tab allows control and calibration of the Measurement Cursor. Left-clicking the mouse anywhere within the image window moves a small cursor, the Measurement Cursor, to the last point clicked upon. The Measurement window calculates the distance between the Measurement Cursor and the center of the Alignment Crosshair, streamlining the accurate location of fiducials in conjunction with the motion application.

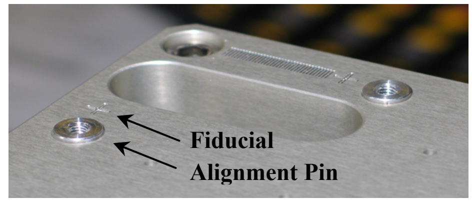



The Schematic tab serves as a guide to the relative locations of the various fiducials and can be referred to as needed during application execution.

## Platen Positioning and Alignment

The platen can be rotated by means of a manual adjustment knob. Resolution of platen rotation is approximately 0.2º per revolution of the adjuster, allowing the average user to achieve less than 10 arc-seconds (0.003°) of rotational error. Alignment of the platen is affected by measuring the motion coordinates of two platen fiducials in a desired direction, whether it be process, cross-process or along an angle. The SAT software automatically calculates the angle between these two coordinates and displays it in units of degrees as well as turns of the platen rotational adjustment knob required to zero the angular offset.

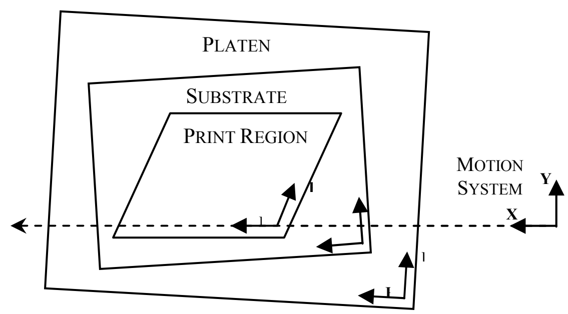
The platen incorporates alignment fiducials and alignment pins around its perimeter. Alignment fiducials are machined into the platen and used by the SAT system to assist in precisely aligning the platen axes to that of the motion system. Any pair of fiducials can be chosen to emphasize a particular axis. Removable alignment pins act as reference edges when placing the substrate on the platen, ensuring a reasonable starting place for the SAT alignment process.




Another feature of the Platen is that of the calibration reticule which is embedded in the platen. The reticule provides a precision reference used to calibrate camera pixels in units of either millimeters or inches. In this way, the camera can be used to measure deposition features.

## Single Sided Alignment

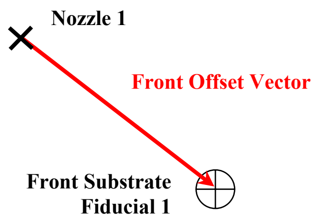
Each component in the printing system can be thought of as having its own set of orthogonal axes that at some microscopic level are never "perfectly" aligned. The figure depicts these coordinate systems with the angles between them exaggerated for clarity. There are three sources of angular error: Platen, Substrate and Printhead. The goal of the SAT is to successively zero these angles such that a square print area resides squarely on the




substrate for both initial and multiple print scenarios. In order to accomplish this, careful attention must be paid to the order and degree of accuracy with each alignment step undertaken.

The first step in deposition process is to align the substrate to the scan axis (X direction). By finding the motion coordinates of two substrate features along the X axis, one can calculate the angle between the line that intersects said features and the x-axis. The 'Measure' tab in the iTi SAT Viewer application greatly simplifies determination of feature location by facilitating measurement of distance. Similarly, calculation and subsequent zeroing of the angular offset is simplified using the 'Align' tab through transfer, calculation and retention of feature coordinates. To zero the angle, the platen rotational adjustment is turned in the direction and number of turns specified in the Align tab. Iteration is required to verify results and the process is complete when the cross-process error is within accuracy requirements for alignment of the image to the substrate. Deposition can then commence per normal procedures.

In order to facilitate subsequent printing on the substrate after removal, the offset vector between a substrate feature and printhead Nozzle 1 needs to be measured and recorded for later reference. Since Nozzle 1 is known from the deposition parameters, one only need find the motion coordinates of the deposited substrate feature/fiducial in order to calculate the offset vector. The 'Offset' tab in the SAT Viewer application facilitates calculation and retention of this vector for later use in re-aligning this particular substrate to the deposition system. The substrate can then be removed from the platen.

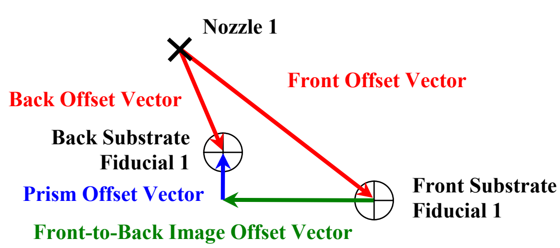


Front Side Alignment Vector

The procedure for depositing second and subsequent passes is to place the substrate on the platen and align the substrate features to the process axis as before. Then the printhead Nozzle 1 location can be calculated using substrate feature coordinates and the Vector Offset associated with the original deposition. In this way, a substrate may be removed for secondary processing and replaced at will as long as the initial Vector Offset is measured and retained.

## Double Sided Alignment

Successful back side alignment requires determination and retention of information in addition to the Front Offset Vector. The figure depicts the relationship between respective coordinates and offset vectors, where Back Substrate Fiducial 1 is that of Front Substrate Fiducial 1 as viewed through the prism assembly when the substrate is flipped for deposition on the back side. The Front-to-Back Image Offset Vector is a property of the deposited image and is non-zero unless located along the axis upon which the image is flipped. The Prism Offset Vector is a SAT system calibration which is defined as the difference in motion coordinates of a fiducial printed on a transparent substrate as viewed from the front and back. Therefore, there exists a mathematical relationship wherein the Back Offset Vector can be determined once the Front Offset Vector is known.

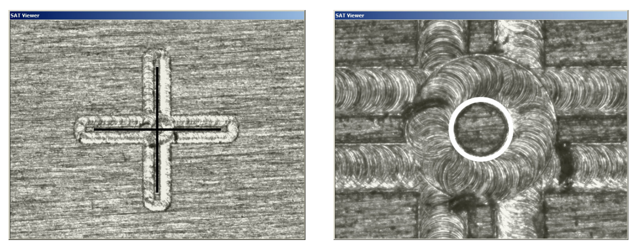


Back Side Alignment Vector Relationships

The SAT Viewer application is used to calculate the Nozzle 1 (deposition start) location when depositing subsequent back side layers on a particular substrate. The procedure is similar to that of front side alignment, but requires advance knowledge of the prism and image offset vectors. As before, this endeavor is greatly simplified using the 'Align' tab. Operationally, the substrate is placed back on the platen and aligned to the x-axis. Then the coordinates of Substrate Fiducial 1 are determined combined with the Back Offset Vector from the previous image for this particular substrate. The calculated Nozzle 1 coordinates represent the location from which deposition is perfectly aligned with the previous image.

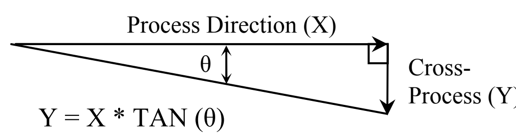
## Accuracy Results

Two degrees of freedom exist where SAT resolution is concerned, the first of which is the continuously-adjusting nature of the platen rotational control. While each turn of the knob affects approximately 700 arc-seconds (0.2º) of platen rotation, there is no minimum step size. However, target selection and camera zoom can significantly affect results, as it is the user's ability to determine whether a fiducial is centered that determines the correct coordinates. A good example is shown in the figure.



Notice that selecting a higher zoom and a circular target affords readily visible resolution improvement, about 4x.

Rotational error can be directly correlated to cross-process error by applying some simple math. The following figure depicts the relationship between platen rotational error and linear error in the cross-process direction. The angle ( ) is determined during




alignment and is found on the 'Align' tab of the SAT Viewer application. The distance in the process direction (X) is the deposition or image length. Practically, the maximum allowable angle is determined from the image length and maximum allowable cross-process error. A rule-of-thumb solution is that each arc-second of angular misalignment results in approximately 5x$10^{-6}$ units per arc-second per (unit) of cross-process error, where units may be millimeters, inches, etc.

## Summary

The substrate alignment tool provides high accuracy alignment of images for materials deposition of ink jet'able fluids on to substrates when double sided or multiple layer depositions are required. It also provides the opportunity to remove substrates from the deposition system for offline processing and being able to replace and align the substrate for additional deposition layers. This is a significant advantage that allows mixing and matching deposition processes other than ink jet. The addition of image analysis software will provide a means of checking the printed images for accuracy and completeness. The SAT together with image analysis could also develop into a powerful tool for real time functional analysis and rework in a production environment.

## References


1. Ross N. Mills, Gregory D. Gates, and Shawn Santana, IS&T Digital Fabrication Conference Proceedings; Denver, Colorado, United States, (2006).
2. Ross N. Mills and William F. Demyanovich, IS&T Digital Fabrication Conference Proceedings; Baltimore, Maryland, United States, (2005).


## Acknowledgement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## Biography

**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.**

**Thomas W. Miller founded Technology Consulting of Boulder in 1996 to provide systems expertise and design services. Since that time, he has executed significant programs in the areas of industrial automation, machine vision, acoustics and optical systems. Prior to founding TCB, he worked for AT&T Bell Laboratories and Lucent Technologies as a Member of Technical Staff, where he contributed to the Undersea Cable, Consumer Products and Federal Systems business units. Mr. Miller is a Professional Engineer and active in the IEEE community.**