Estimating Combined Servo and Galvo Motion Accuracy

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In modern motion control systems, the primary figure of merit is often the global accuracy that may be achieved on the workpiece surface. However, when configuring the motion control architecture for more advanced features, such as Infinite Field of View (IFOV), characterizing each element of the systemic errors can be very challenging, because such complex system have not only primary error contributors, but also secondary errors which result from using a combination of stages and galvanometers together. This white paper details how to characterize the constituent error elements and suggests a means of predicting overall system errors for IFOV-enabled motion control platforms.

In assessing the errors, they may be segregated into 3 bins:

1. Errors from the underlying servo stages
2. Errors from the galvanometer (including those errors caused by incoming laser beam misalignment)
3. Systemic errors resulting from using a combined system of stages and galvos together

Before the experimental data shown below was gathered, the underlying linear motor servo stages were calibrated using a 2D correction (i.e., plane mirror and dual laser interferometers). This optimizes their static error performance by removing not only "straight line" errors from the stage encoders, but also correcting for errors induced by yawing motion of the stages and by non-orthogonal alignment of the stages to one another. The work point for this calibration was selected to be underneath the center of the galvanometer's field of view. Resulting errors from the stages alone were less than 10 microns, with a vector sum of 5.26 microns (see Figure 1, below), and X / Y direction errors are noted explicitly in the data sets
shown later in this paper.

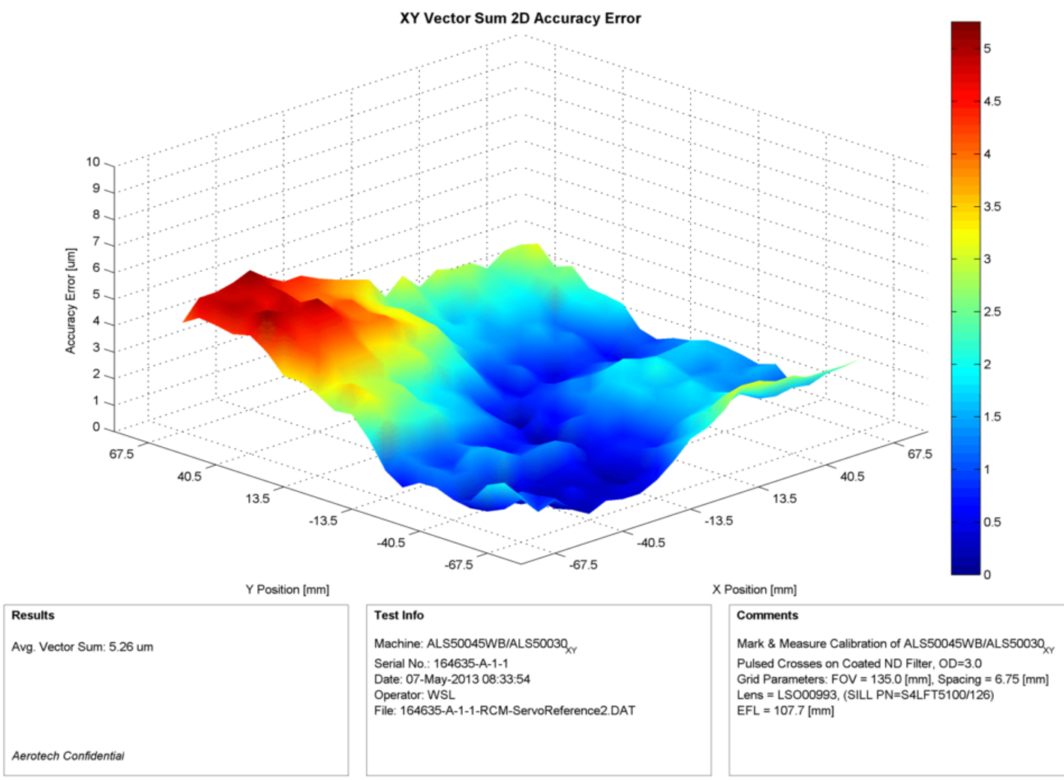


Figure 1**.** *Servo Stage Vector Error*

The galvo itself was calibrated using a "mark-and-measure" technique. A silver-coated glass substrate was marked using an IR laser (1070 nm wavelength) to produce marks whose positions were which were measured under high magnification. The errors between the marks' locations and their intended positions were used iteratively to produce a series of correction tables. The resulting errors are shown below (vector error of 2.06 microns).

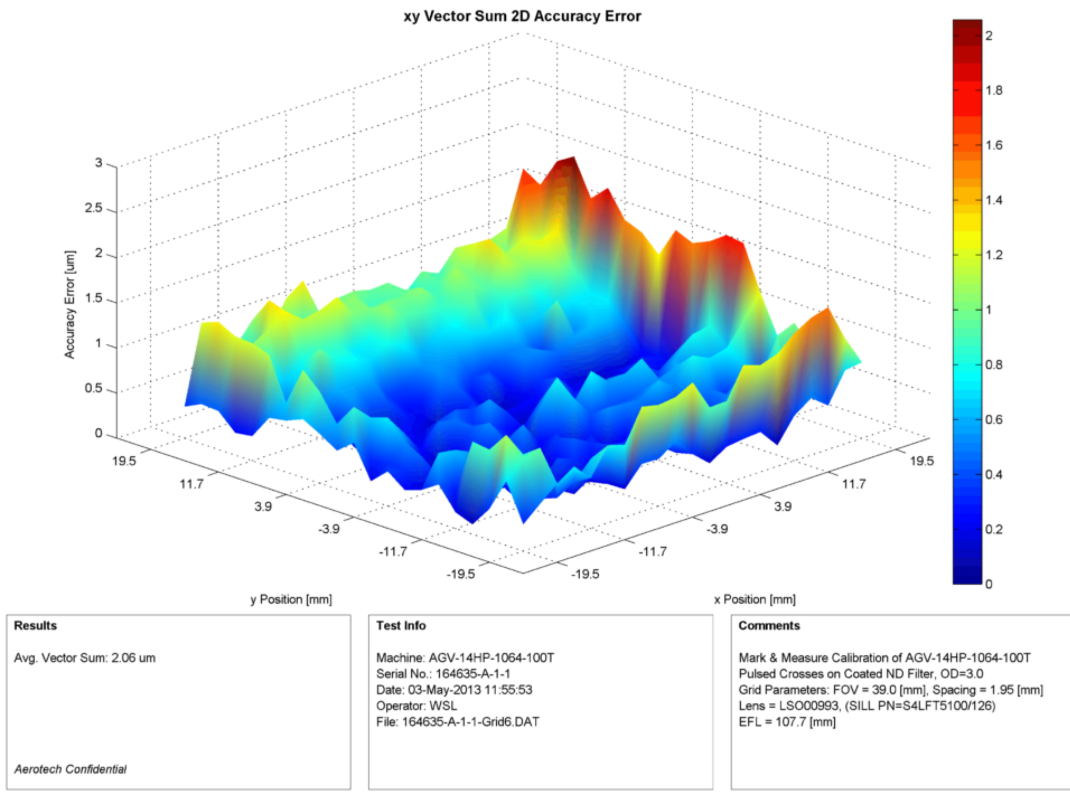


Figure 2. *Galvanometer Vector Error*

Perhaps the most interesting error to analyze is that produced by the combination of both motion subsystems. Such errors have a number of sources, including:

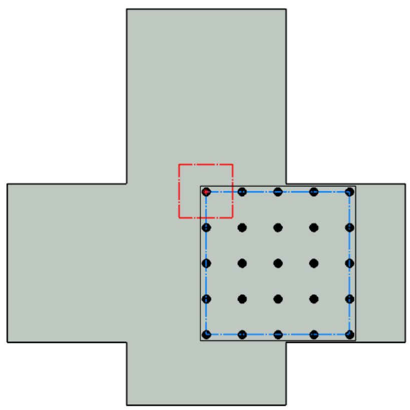
1. Rotational misalignment of the stage travel directions to the galvanometer axes
2. Co-planarity errors of the stage XY travel plane to the galvo focal plane
3. Secondary errors (notable stage yaw) not corrected due to the fact that the stage 2D calibration was done at a single work point, while the actual laser marking could be at any point within the galvanometer's field of view.

The actual process of determining these systemic errors used "random combined motion grid marking," and is depicted below.

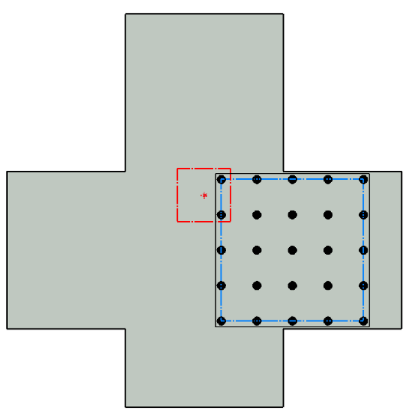
The following series of illustrations are used to demonstrate how the "Random Combined Motion Grid" is created using the combined motion of both the servo axes' coordinate frame and the galvo scanner's coordinate frame. They show the relative positions of the servo axes' travel, the galvo axes' field of view, and the actual grid to be marked by the random combined motion test program. The grey outline represents the stage assembly and the black square represents the marking substrate (as carried by the upper stage axis). The black dots represent the grid to be marked. The grid's overall size, the dashed blue square, is equal to the size of the servo stages' total travel minus the galvo's total field of view (for our test case this was 96.0 x 96.0 [mm]). The red dashed square represents the total field of view of the scanner, which in this case is 39.0 x 39.0 [mm], and the red dot within the AGV's field of view represents the location of the laser spot.

Procedure

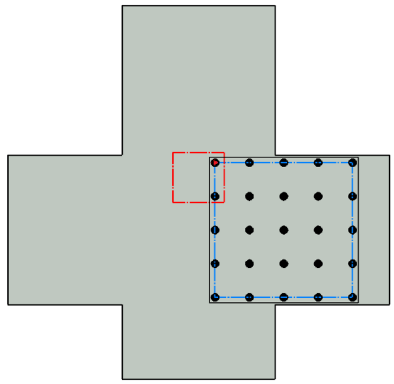
1. The servo and galvo axes begin at their home position, with the substrate centered underneath the AGV's field of view.
2. The servo axes move the first mark location on the substrate underneath the laser spot with the galvo axes at their home position.



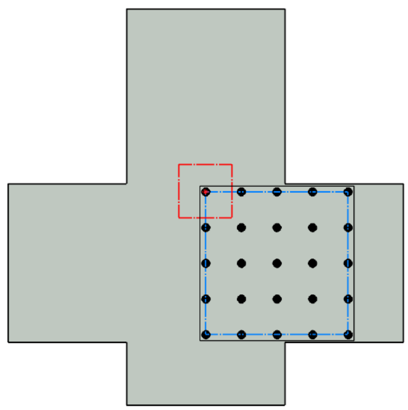
3. The servo axes move a random percent of the size of the galvo's field of view in a random direction.



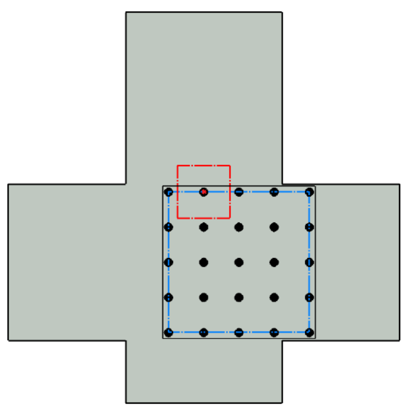
4. The galvo axes then perform an opposing move. If the coordinate frames are perfectly aligned and congruent, the motions of the two sets of axes will null each other leaving the laser spot in the correct location within the grid for a mark to be placed.



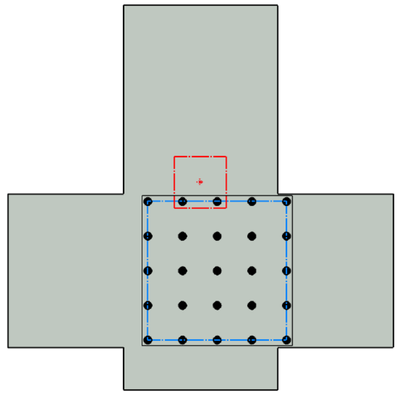
5. After the creation of the mark, the servo and galvo axes undo the random motion, bringing the mark location back underneath the center of the galvo's field of view.



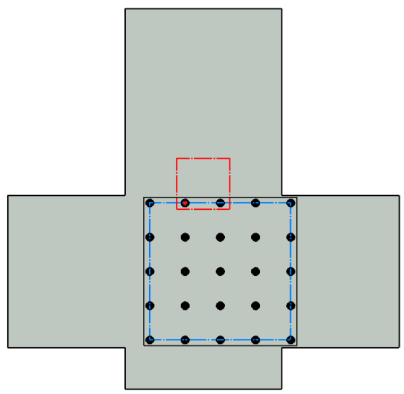
6. The servo axes move the second mark location on the substrate underneath the laser spot with the galvo axes at their home position.



7. The servo axes repeat Step 3, moving a percentage of the galvo's field of view in a random direction.



8. The galvo axes once again make an opposing move, nulling the motion and placing the laser spot correctly at mark location #2.



9. The process is repeated until the grid is completed. The resultant grid is then measured with the same inspection station.

The resulting combined measured errors are displayed in Figure 3 below.

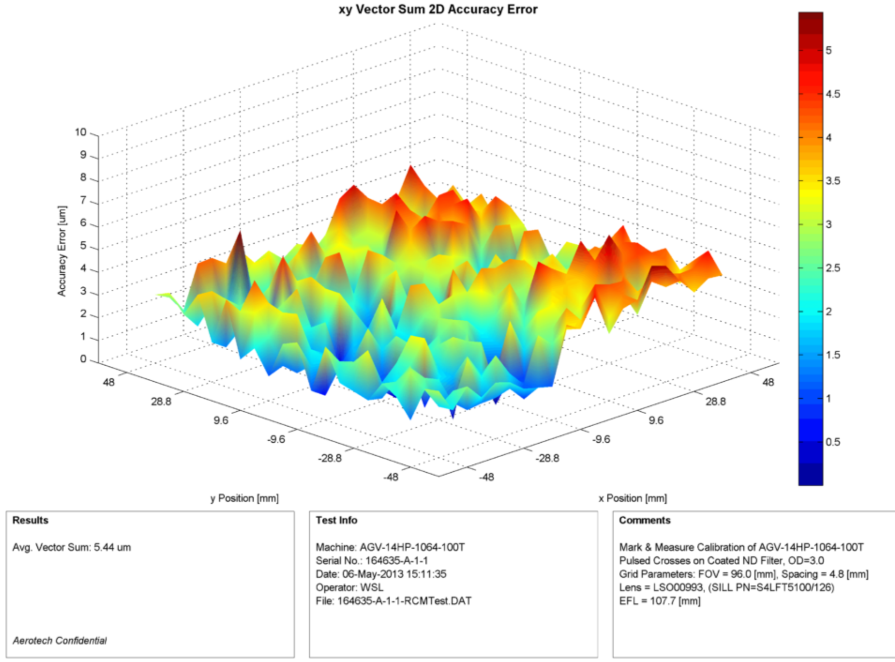


Figure 3. *Galvanometer Vector Error*

Furthermore, a statistical combination of these errors may be compiled, as shown below.

Testing Summary Table: Combined Servo and Galvo Motion Accuracy						
Grid	**X Axis Accuracy, 4σ [µm pk-pk]**	**X Axis Accuracy, Raw [µm pk-pk]**	**Y Axis Accuracy, 4σ [µm pk-pk]**	**Y Axis Accuracy, Raw [µm pk-pk]**	**Vector Error, Raw [µm peak]**	**Orthogonality [arc-sec]**
Independent AGV Grid	1.61	2.45	1.77	2.75	2.06	1.86
Independent Servo Grid	4.60	6.00	6.55	7.71	5.26	9.10
Random Combined Motion Grid #1	4.97	8.10	4.69	6.72	5.44	10.68
Random Combined Motion Grid #2	6.00	7.95	4.83	7.13	5.29	7.67
Note: 4σ error value represents 95.45% confidence of peak-to-peak error						

Conclusions

When examining the measurement results of the three grids compared in this test, it is evident that the overall accuracy and error pattern of the random combined motion grid is largely dictated by the servo axes. This is not unexpected, as the servo axes account for a much larger portion of the overall movement of the random combined motion grid, and they are also the largest contributor of error in the system. The results of this testing allow for reasonably confident approximation of laser marking performance when using combined motion systems, and should help in the decision making process as to which stages are appropriate given the goals of a given application. Most interestingly, the 4*Sigma error distribution for each grid, as well as the vector error, suggests that an RSS value of galvo and servo axis error can be used to approximate the combined error of the two independent coordinate frames. Thus system designers should be able to estimate errors of a combined system merely by understanding the foundational (servo and galvo) errors.

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