Geometrically Compensated Measurement with a Laser Digitizer Equipped CMM

John O. Harris and Allan D. Spence*
McMaster University, Hamilton, Ontario, Canada

1. Introduction: Industrial designers frequently sculpt conceptual freeform shapes in wood or clay. The model is then digitized to create a Computer-Aided Design (CAD) model. During manufacturing, there is an industrial need to measure parts such as automotive sheet metal body panels for dimensional conformance. Because of their high data collection rates, laser digitizers are commonly chosen as the digitizing device. The digitizer is attached to a Coordinate Measuring Machine (CMM) in place of the conventional touch trigger probe, and reoriented as required to cover the large and complex part surface. High accuracy is required so that the geometric data collected from each orientation can be merged into a common part coordinate system.

Currently, the accuracy of such systems is limited by the lack of an integrated geometric error compensation system. That is, there is no correction of the laser digitizer point coordinates to compensate for the varying geometric errors encountered at different locations within the CMM volume. This paper reports progress towards achieving such as integrated system.

2. Laser Digitizer Description: The laser digitizer used in this paper is a Hymarc Hyscan 45C [1]. A real-time microprocessor system obtains points from the sensor in the local digitizer $[U \quad V \quad W]^T$ coordinate system (Figure 1). Simultaneously, uncompensated CMM $[D \quad E \quad F]^T$ axis coordinates are obtained using opto-isolators connected to the scale electronics. These six coordinates are recorded to a data file for later offline geometric error compensation.

3. Position Error: A conventional CMM has three carriages mounted in orthogonal directions. For this research, a moving bridge style Z on Y on X configuration was used. To obtain the volumetric error parameters of a CMM, the linear, straightness, and angular errors of a CMM are typically obtained using a laser interferometer, and squareness errors are obtained using a double ball bar. The error map and correction scheme followed herein is based on Kunzman [2]. At a given scale position relative to the home position $[D \quad E \quad F]^T$, the geometric error equations are:

$$
\begin{aligned}
e_X &= \delta_X(D)+\delta_X(E)+\delta_X(F)-E\cdot\varepsilon_Z(D)+F\cdot\varepsilon_Y(D)+F\cdot\varepsilon_Y(E)-E\cdot S_{XY}-F\cdot S_{XZ} \\
e_Y &= \delta_Y(D)+\delta_Y(E)+\delta_Y(F)-F\cdot\varepsilon_X(E)-F\cdot\varepsilon_X(D)-F\cdot S_{YZ} \\
e_Z &= \delta_Z(D)+\delta_Z(E)+\delta_Z(F)+E\cdot\varepsilon_X(D)
\end{aligned}
\tag{1}
$$

where the error factor terms are obtained from Table 1.

4. Orientation Error: Unlike single point acquisition touch trigger probes, the laser digitizer collects line data in a local scan plane. As the sensor is translated, the scan plane orientation varies due to the CMM volumetric errors. Including this effect when correcting the uncompensated digitizer data is the primary goal of the reported research. The initial step, for every intended laser digitizer orientation, is to calibrate with respect to a reference optical sphere. This Hymarc defined procedure establishes the transformation

* Corresponding author: adspence@mcmaster.ca, Department of Mechanical Engineering, McMaster University, Hamilton, Ontario, Canada L8S 4L7

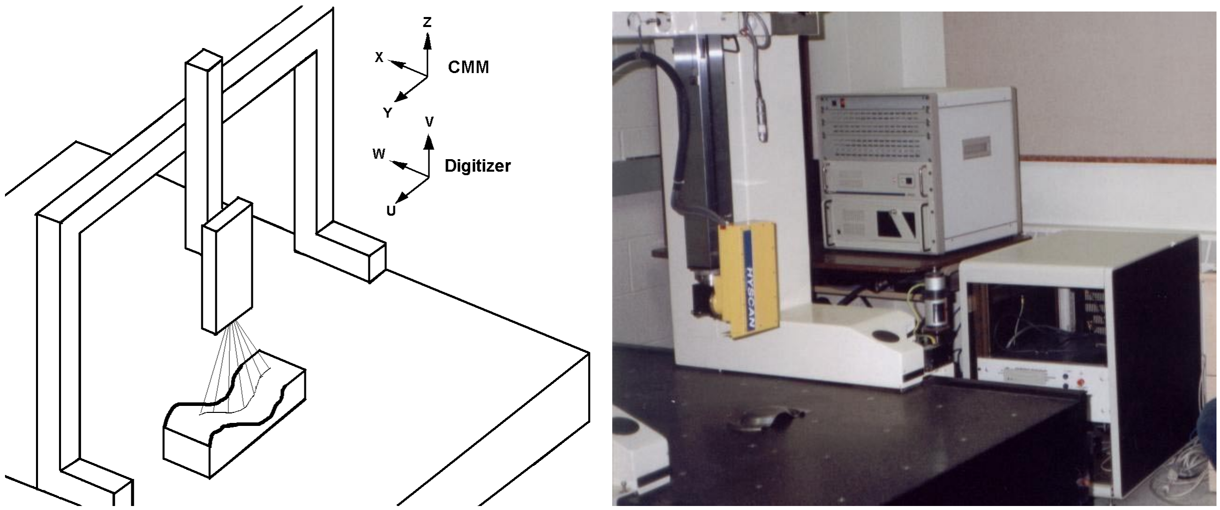

Figure 1: Hyscan 45C laser digitizer and coordinate systems

Table 1: CMM error table

X axis	Position Error (μm)			Orientation Error (arc-seconds)		
D scale (mm)	$\delta_X(D)$	$\delta_Y(D)$	$\delta_Z(D)$	$\varepsilon_X(D)$	$\varepsilon_Y(D)$	$\varepsilon_Z(D)$
0	0	0	0	0	-0.6	-0.1
100	3	0	0	0	-0.8	0.5
200	2	0	0	0	-0.95	0.25
300	5	0	0	0	-0.5	0.1
400	8	0	0	0	0.15	-0.1
500	11	2	0	0	0.65	0.55
600	11	-1	0	0	0.6	0.95
700	11	2	0	0	0.95	1.55
800	12	0	0	0	1.45	1.75
900	12	0	0	0	1.4	2
Y axis	Position Error (μm)			Rotational Error (arc-seconds)		
E scale (mm)	$\delta_X(E)$	$\delta_Y(E)$	$\delta_Z(E)$	$\varepsilon_X(E)$	$\varepsilon_Y(E)$	$\varepsilon_Z(E)$
0	0	0	0	-0.35	0	-0.2
100	0	11	0	-1.15	0	0.1
200	-7	16	1	-0.7	0	0.05
300	-11	25	1	-1.05	0	0.1
400	-7	33	-1	-1.45	0	0.4
500	2	38	-1	-1.6	0	0.95
Z axis	Position Error (μm)			Rotational Error (arc-seconds)		
F scale (mm)	$\delta_X(F)$	$\delta_Y(F)$	$\delta_Z(F)$	$\varepsilon_X(F)$	$\varepsilon_Y(F)$	$\varepsilon_Z(F)$
-500	0	0	0	-1.5	-0.15	0
-400	0	0	0	-2.4	0.55	0
-300	0	0	-4	-1.05	0.4	0
-200	0	0	-2	-3.3	-0.45	0
-100	0	-2	-2	-3.7	-1.6	0
0	0	0	-5	-3.8	-3.2	0

Squareness Errors (arc-seconds)
S_{XY} =-169.397
S_{YZ} =33.979
S_{ZX} =-25.984

Note: Data was collected at 25 mm increments. Only the 100 mm increments are shown.

$$ {}^{R}\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \begin{bmatrix} & [R] & & \begin{matrix} D-D_0 \\ E-E_0 \\ F-F_0 \end{matrix} \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} U \\ V \\ W \\ 1 \end{bmatrix} \tag{2} $$

that relates $[U \quad V \quad W]^T$ to the uncompensated position ${}^{R}[X \quad Y \quad Z]^T$. The rotation matrix $[R]$ corrects for the misalignment between $[U \quad V \quad W]^T$ and the CMM axis directions at the location of the reference optical sphere, and $[D_0 \quad E_0 \quad F_0]^T$ is the scale reading when $[U \quad V \quad W]^T = [0]$. This information is automatically stored within the Hymarc data point file.

By using three separate digitizer orientations, the distance between the $[U \quad V \quad W]^T$ origin and the sensor (CMM geometric error compensation map) origin was determined to be $[U_1 \quad V_1 \quad W_1]^T = [2.196 \quad 265.320 \quad 129.826]^T$ mm. Using this information, the transformation

$$ {}^{P}\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \begin{bmatrix} & [R] & & [R]\cdot\begin{bmatrix} -U_1 \\ -V_1 \\ -W_1 \end{bmatrix} \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} U \\ V \\ W \\ 1 \end{bmatrix} \tag{3} $$

establishes the digitized point position relative to the pose origin. Application of the transformation

$$ {}^{H}\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \begin{bmatrix} [X_P] & [Y_P] & [Z_P] & \begin{matrix} D+e_X \\ E+e_Y \\ F+e_Z \end{matrix} \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot {}^{P}\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \tag{4} $$

where

$$ [Z_P] = \begin{bmatrix} \dfrac{\tan\varepsilon_Y}{\sqrt{1+\tan^2\varepsilon_X+\tan^2\varepsilon_Y}} \\ \dfrac{-\tan\varepsilon_X}{\sqrt{1+\tan^2\varepsilon_X+\tan^2\varepsilon_Y}} \\ \dfrac{1}{\sqrt{1+\tan^2\varepsilon_X+\tan^2\varepsilon_Y}} \end{bmatrix}; [X_P] = \begin{bmatrix} \dfrac{1}{\sqrt{1+\tan^2\varepsilon_Z+(\tan\varepsilon_X\cdot\tan\varepsilon_Z+\tan\varepsilon_Y)^2}} \\ \dfrac{-\tan\varepsilon_Z}{\sqrt{1+\tan^2\varepsilon_Z+(\tan\varepsilon_X\cdot\tan\varepsilon_Z+\tan\varepsilon_Y)^2}} \\ \dfrac{-(\tan\varepsilon_X\cdot\tan\varepsilon_Z+\tan\varepsilon_Y)}{\sqrt{1+\tan^2\varepsilon_Z+(\tan\varepsilon_X\cdot\tan\varepsilon_Z+\tan\varepsilon_Y)^2}} \end{bmatrix}; [Y_P] = [Z_P]\times[X_P] $$

and $\varepsilon_j = \sum_{i=D,E,F} \varepsilon_j(i);\ j = X, Y, Z$, provides the final, fully compensated digitized point position.

5. Measurements: To verify the correctness of the algorithms developed in Section 4, measurements were made with and without compensation on an ASME B89.4 [3] style optical ballbar. The spheres were 76.25 mm in diameter and the bar was approximately 404 mm between the sphere centers.

The CMM errors were previously measured and stored (Table 1). For each intended orientation, the laser digitizer was calibrated to obtain the equation (2) parameters. The ballbar was then measured at the 20 specified ASME B89.4 [3, Figure 26] positions. For each point, the $[U \quad V \quad W]^T$ and $[D \quad E \quad F]^T$ coordinates were collected. Approximately 17,000 sphere points were recorded at each end of the ballbar. The matrix procedure described in Section 4 was used to compensate each point, and the sphere centers were located using orthogonal least squares. Results are shown in Figure 2.

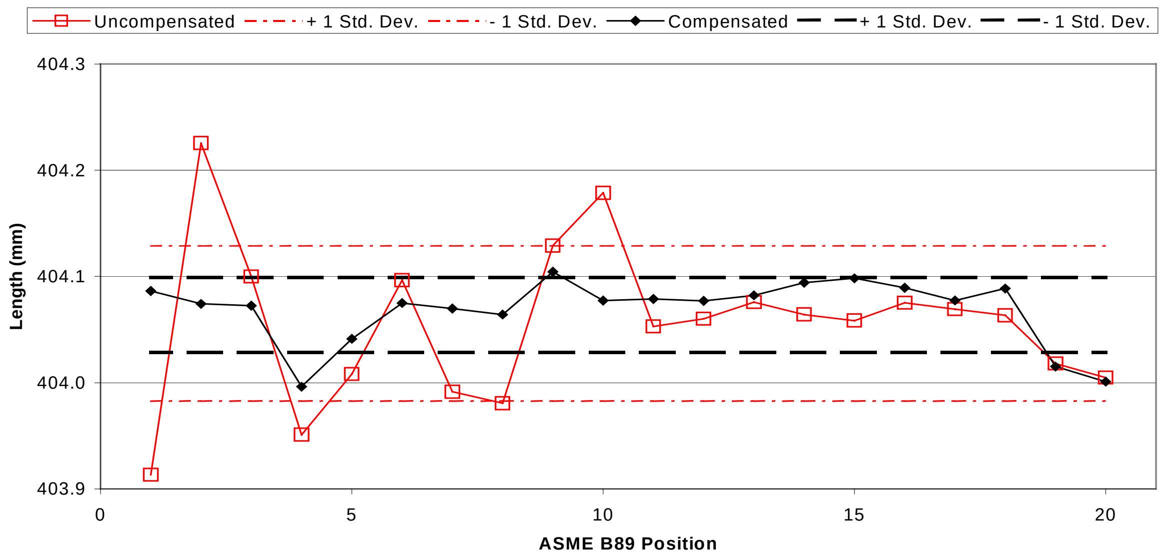

Figure 2: ASME B89 Figure 26 Ballbar Accuracy Test

6. Discussion: The most significant CMM flaw is the 160 arc second *XY* squareness error. This shows up particularly at positions 1 and 2. The compensation procedure handles this well. Positions 4, 19 and 20 give the smallest apparent corrected length of the ballbar.

The uncompensated measurements had a mean of 404.056 mm and a standard deviation of 73 µm. The compensated measurements had a mean of 404.068 mm and a standard deviation of 31 µm. Based on the published laser digitizer accuracy, and the measured CMM error, this 60% improvement in the data standard deviation is consistent with expectations.

7. Conclusions: To implement the integrated error compensation, the scan plane coordinates and the CMM axis scale positions were recorded simultaneously in real time and compensated for pose position and attitude. There is a 60% improvement in the accuracy of the data.

As well as error compensation algorithms, good operator technique in careful camera alignment calibration and scanning path planning are important to obtaining improved accuracy using a laser digitizer on a CMM.

This paper has shown an error compensation technique for laser digitizer measurements that will benefit CAD applications and quality assurance.

8. Acknowledgements: The authors are grateful to NCE-Auto 21 for financial support, CFI/OIT for equipment, and to Omni-Tech CMM Services for their support in measuring the CMM errors.

9. References:

[1] "Hyscan 45C 3-D Laser Digitizer", Hymarc 3D Vision Systems, Nepean, ON.

[2] Kunzman, H.; Ni, J.; Waldele, F. "Accuracy Enhancement", Coordinate Measuring Machines and Systems, Bosch, John A.(ed.), Marcel Dekker, Inc., New York., 1995.

[3] ASME B89.4.1 "Methods for Performance Evaluation of Coordinate Measuring Machines", An American National Standard., 1997.