Dynamic Metrology and ASTM E57.02 Dynamic Measurement Standard

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Abstract

Optical tracking systems[1] are used in a wide range of fields. The market for optical tracking systems has dramatically increased over the past several years to $1.2B revenue in 2014. This paper describes the new ASTM E3064 Standard test method procedures for optical tracking systems and will outline the theoretical basis for the analysis of the data from these systems. The paper will also verify the performance of an example 12 camera optical tracking system using these standard procedures and related analysis. An artifact, developed at the National Institute of Standards and Technology, was verified by a coordinate measurement machine and then used in two experiments to verify the test method. This and other in-depth papers are intended to be base references for ASTM E3064.

Keywords: optical tracking, coordinate measurement machine, ASTM E3064 standard, reproducible performance, test methods, artifact

1 Introduction

Optical tracking systems measure the three-dimensional, static and dynamic position and orientation of multiple markers attached to objects within a measurement space. Optical tracking systems are used in a wide range of fields including: neuroscience[i], biomechanics[ii], robotics[iii], and automotive[iv] assembly. The market for optical tracking systems has dramatically increased over the past several years to $1.2B revenue in 2014 with annual growth of nearly 53% from 2009 to 2014.[v, vi, vii] Potential users of optical tracking systems often have difficulty comparing systems because of the lack of standard performance metrics and test methods, and therefore must rely on vendor claims regarding the system's performance, capabilities, and suitability for a particular application. The ASTM International Committee E57 on 3D Imaging Systems' subcommittee on test methods addressed the static performance measurement of optical tracking systems[viii]. Recently, the ASTM E57.02 subcommittee task group has developed a new standard test method, "ASTM E3064 Standard Test Method for Evaluating the Performance of Optical Tracking Systems that Measure Six Degrees of Freedom (6DOF) Pose"[ix]. The new test method presents metrics and procedures for measuring, analyzing, and reporting the errors and deviations of dynamic optical tracking

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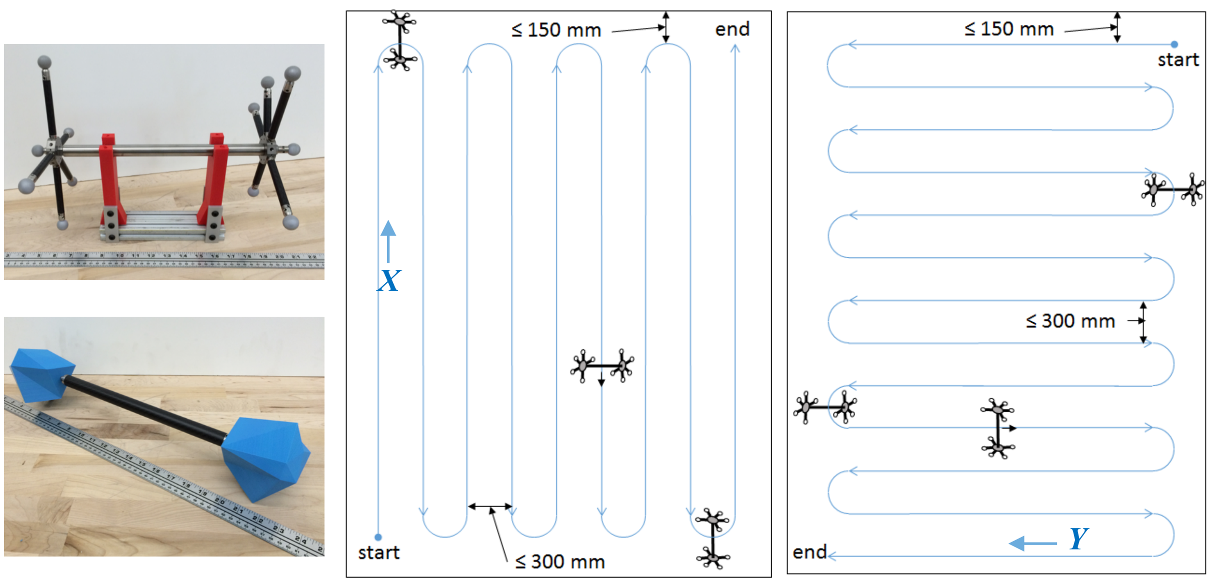
systems. An artifact, developed at the National Institute of Standards and Technology (NIST) and shown in Figure 1 a - top, was first used to measure a multi-camera system and then expanded by the ASTM E57.02 task group to apply to all types of optical tracking systems. Figure 1 a – top shows an artifact that is used for systems that operate based on active or retroreflective markers and Figure 1 – bottom shows an artifact that can be used for systems that use geometric features as markers. The artifact description in the standard allows for a variety of markers to fit the optical tracking system's measurement method. The end markers are measured relative to one another in each right and left cluster on the bar and combined through mathematical analysis to output the resulting bar length throughout the measurement space.

This proposed standard provides a common set of metrics and a test procedure for evaluating the performance of optical tracking systems and may help to drive improvements and innovations. The standard will also allow users to assess and compare the performance of a candidate optical tracking system and to determine if the measured performance results are within the specifications with regard to the application requirements.

This paper describes the new ASTM E3064 Standard test method procedures for optical tracking systems and will outline the theoretical basis for the analysis of the data from these systems. The paper will also verify the performance of an example, 12 camera optical tracking system. These experiments were conducted using the standard procedures and the analysis method using the artifact shown in Figure 1a (top), which was measured using a coordinate measurement machine (CMM). A second method provided in the standard, not part of this paper, allows the measurement results to be used without prior knowledge of artifact measurement from a CMM or other similar machine. This and other in-depth papers are expected to be the base references for ASTM E57.02.



a b c

Figure 1 – (a) Artifacts to measure optical tracking system performance. (b) Forward-back (aligned with the X axis) and (c) side-to-side (aligned with the Y axis) paths and dimensions for moving the artifact in a test space. Reprinted, with permission from ASTM E3064-16 Standard Test Method for Evaluating the Performance of Optical Tracking Systems that Measure Six Degrees of Freedom (6DOF) Pose, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

2 Metrics and Test Method

ASTM E3064 provides statistically-based performance metrics and a test procedure to evaluate the dynamic performance of optical tracking systems. Measurements from optical tracking systems include inherent positional and orientation angle errors relative to fixed optical measurement components. Metrics are therefore the static and dynamic position and orientation of tracked objects. Beyond the scope of this paper are metrics that are currently being researched which include system latency and maximum dynamic measurement capability.

The test procedure outlined in E3064 measures the relative pose between two sets of markers that are rigidly attached to the ends of a metrology bar as shown in Figure 1a. The relative pose is then decomposed into positional and angular components and measurement errors are calculated by comparing results to a known metrology bar length of the artifact.

The artifact includes a 300 mm long metrology bar with markers rigidly attached to each end. The bar is called a 'metrology bar' since it has stiffness and thermal expansion characteristics to allow deflection of less than or equal to 0.01 mm. Example metrology bars are made of carbon fiber or titanium that meet the mandatory minimal deflection characteristic. One form of artifact includes two clusters of passive, reflective, spherical (see Figure 1a top) or active, light-emitting-diode (LED) markers located at the ends of the metrology bar. Another form uses reduced pose ambiguity cuboctahedron[x] (see Figure 1a bottom) markers. Both types of markers must be contained within hemispherical volumes of 100 mm maximum radius from the ends of the bar.

The basic procedure for determining the pose measurement error of an optical tracking system first includes rough (hand-held) alignment of the X and Y axes (Figure 1) and Z axis (aligned with the vertical axis) within the test volume to be measured. The options for the test volume are: (1) 3000 mm long x 2000 mm wide x 2000 mm high, (2) 6000 mm long x 4000 mm wide x 2000 mm high, and (3) 12000 mm long x 8000 mm wide x 2000 mm high.

The optical tracking system tracks the metrology bar as it is moved throughout the test volume along the two patterns shown in Figure 1b and Figure 1c for three trials. The metrology bar in each trial corresponds to one of the three orientations shown in Figure 2. The centroid of the metrology bar is to remain at approximately 1 m above the test volume floor and should be moved at approximately the walking speed of 1.2 m/s ± 0.7 m/s. The metrology bar length is used as a guideline for determining both the distance between the boundary lines and the limits of the test volume. The data from these three trials are then combined into one data set.

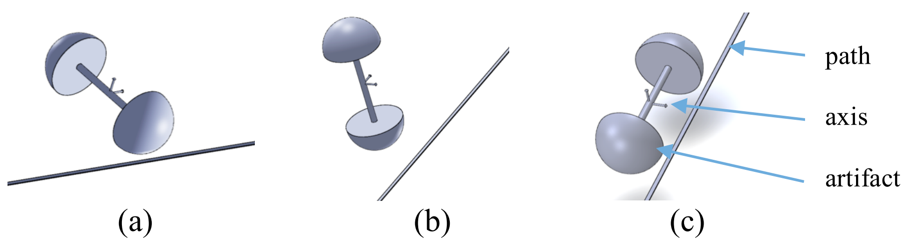


Figure 2: The artifact (shown with axes on the bar centroid) orientations with respect to the path: (a) perpendicular to the path segments in the plane of motion, (b) perpendicular to the path segments and normal to the plane of motion, and (c) in-line with the path segments in the plane of motion. The artifact shown in Figure 1 ((a) and (b)) is oriented with respect to the path as in (a) perpendicular to the path segments in the plane of motion. This caption includes descriptions directly from E3064. Reprinted, with permission from ASTM E3064-16 Standard Test Method for Evaluating the Performance of Optical Tracking Systems that Measure Six Degrees of Freedom (6DOF) Pose, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

The data gathered from the optical tracking system (OTS) consist of the 6DOF pose of the left and right ends of the artifact at time *t* represented as the homogeneous matrices

$$_{OTS}\hat{H}_{Left}(t) = \begin{bmatrix} \hat{R}_{Left}(t) & \hat{T}_{Left}(t) \\ 0 & 1 \end{bmatrix} \text{ and } _{OTS}\hat{H}_{Right}(t) = \begin{bmatrix} \hat{R}_{Right}(t) & \hat{T}_{Right}(t) \\ 0 & 1 \end{bmatrix}.$$

Then the relative pose between the left and right markers is defined as

$$_{Left}\hat{H}_{Right}(t) = {}_{OTS}\hat{H}^{-1}_{Left}\,{}_{OTS}\hat{H}_{Right} = \begin{bmatrix} \hat{R}_{Left}(t) & \hat{T}_{Left}(t) \\ 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} \hat{R}_{Right}(t) & \hat{T}_{Right}(t) \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} \hat{R}(t) & \hat{T}(t) \\ 0 & 1 \end{bmatrix},$$

where $\hat{R}(t)$ is the 3x3 rotation matrix describing the relative orientation between the left and right markers and $\hat{T}(t)$ is the 3x1 vector describing the relative translation between the left and right markers. The angle of rotation can then be described as

$$\hat{\theta}(t) = 2 * \operatorname{asin}\left(\sqrt{\hat{q}_x^2(t) + \hat{q}_y^2(t) + \hat{q}_z^2(t)}\right),$$

where $\left(\hat{q}_w(t), \hat{q}_x(t), \hat{q}_y(t), \hat{q}_z(t)\right)^T$ is the unit quaternion representation of $\hat{R}(t)$ and $\hat{q}_w(t)$is the scalar component of the quaternion.

If the relative pose between the left and right markers has been measured by a reference system and represented as

$${}_{Left}H_{Right} = \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} I & T \\ 0 & 1 \end{bmatrix},$$

then the position error at time *t* can be defined as

$$e_{p(t)} = \|\hat{T}(t)\| - \|T\|,$$

and the orientation error at time *t* can be defined as

$$e_{o(t)} = \hat{\theta}(t) - 0 = \hat{\theta}(t).$$

Statistics on these errors include:

Root Mean Square	RMS	$\sqrt{\frac{1}{N}\sum_{t=1}^{N} e_t^2}$
Maximum Error	e_{max}	$\max(\lvert e_1\rvert, \lvert e_2\rvert, \ldots, \lvert e_N\rvert)$
Percentile Error	$E(p)$	$\begin{cases} E_k + d(E_{k+1} - E_k), & 0 < k < N \\ E_1, & k = 0 \\ E_N & k \geq N \end{cases}$

Here, e_t denotes either the positional error $e_{p(t)}$ or the orientation error $e_{o(t)}$. In addition, the percentile error *E(p)* on the ordered set $\{E_1, E_2, \ldots, E_N\}$ is constructed from rearranging the set of errors $\{\lvert e_1\rvert, \lvert e_2\rvert, \ldots, \lvert e_N\rvert\}$ by increasing value. Moreover,

$$\frac{p}{100}(N+1) = k + d,$$

where *k* is an integer and $0 \leq d < 1$. The specific percentile errors reported are *E(99.7), E(95),* and *E(50).*

3 Experiments

Experiments were performed (A) to test the motion of optical tracking system camera mounts and (B) to test the ASTM E3064 standard test method. Optical tracking system camera mounting is critical to providing the best system calibration possible. If there is camera motion, the system measurement will provide less certainty than with fixed camera mounts. Hence, a measurement of camera motion is useful to determine how much motion the reference frame including all cameras provides. The authors measured the motion of two cameras mounted in worst-case locations for the reader to further understand this concept.

For experiment A, two optical tracking system camera mounts were tracked for 24 hours each using a laser tracker with an uncertainty of approximately 10 µm[xi]. Magnetic retro reflector mounts were glued to the two camera mounts located near the center of the longest walls of the rectangular laboratory. The laboratory, shown in Figure 3, has 12 optical tracking system cameras mounted at a height of 4.3 m on 6.7 m high perimeter walls. The laser tracker was programmed to take a data point each second for a total of 86,400 data points. The inside laboratory environment remained at a relatively constant room temperature and humidity. However, during the outside wall motion measurement, the outside temperature changed by approximately 30° F between day and night. The day was rainy, cloudy with no sun and a high of approximately 55° F. Optical tracking system calibration and experiment B were not, however, performed during the same day as experiment A since the laser tracker beam would have been obstructed during calibration and the experiment.

Before experiment B, an optical tracking system calibration routine was performed. The routine included ensuring that extraneous reflectors were covered. These included a set of thirteen reflectors, mounted on the perimeter walls for automatic guided vehicle (AGV) navigation, were covered. The AGV with onboard robot arm, including reflective markers detectable by the optical tracking system, were also covered with a large sheet of black plastic. Also, the floor was covered with black plastic due to reflections onto the floor tile caused by infrared light emitting diodes surrounding each camera. When the reflections were minimized, the tracking system was calibrated by waving the manufacturer's calibration wand throughout the work volume until the system termed the calibration as 'exceptional' meaning a high confidence in the calibration.

Experiment B used the artifact shown in Figure 1a top. The paths shown in Figure 1b were then walked at an estimated speed of 1.2 m/s ± 0.7 m/s (as noted by the standard) over an area of approximately13 m by 6 m while the optical tracking system tracked the artifact motion. The artifact was held at a height of approximately 2 m and oriented as in the Figure 2a. This test area is similar to the third test volume described in Section 2: Metrics and Test Method. After both X and Y paths were walked with the artifact in the first artifact orientation, the experiment was repeated with the artifact held in the orientations shown in Figure 2b and Figure 2c. The data were then combined into a single data set, as required in the standard, and analyzed. The test method was then repeated for a second trial on another day after recalibration to ensure that experiment B was properly performed and that the data retrieved were similar to the first day experiment B. The total experiment B took roughly 12 minutes.

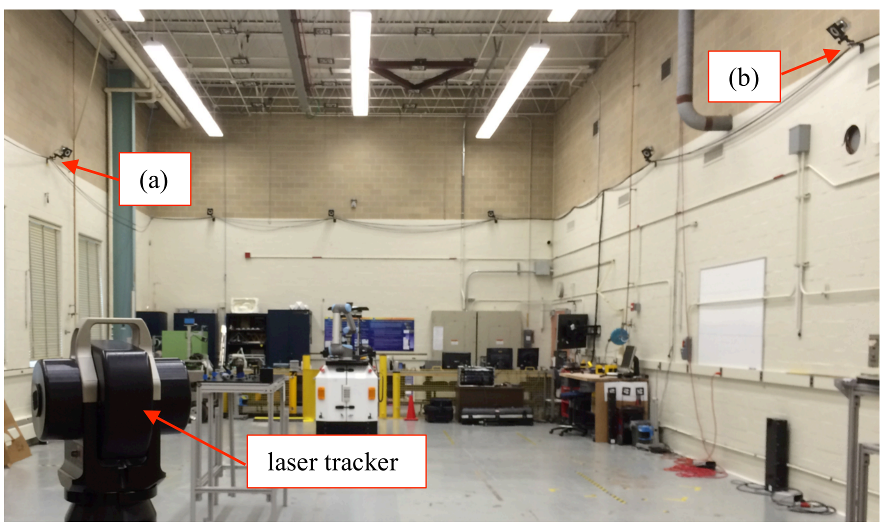
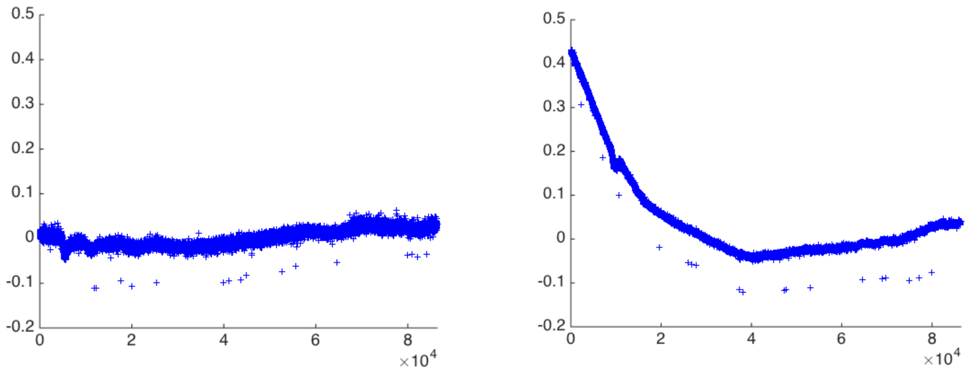


Figure 3. Laser tracker measuring a laboratory, outside-wall, mount (a) that supports an optical tracking system camera. On the right is the (b) inside-wall mount that was measured.

4 Experimental Results

For experiment A, the laser tracker provided results over 24 hours where, as expected, the inside wall moved much less than the outside wall. The data is shown in Figure 4 for both wall measurements.



a b

Figure 4. Laser tracker data from measurement of two camera mounts supporting optical tracking system cameras inside the laboratory on (a) an inside block wall and (b) an outside block wall. The horizontal axis is in sample points and the vertical axis is in mm.

For example, disregarding outliers, wall motion data spanned between approximately + 0.04 mm and - 0.05 mm for the inside wall and between approximately + 0.43 mm and - 0.05 mm maximum for the outside wall. Outside wall measurement began at 2 PM. Most motion of the outside wall was between 2 PM and 2 AM as shown in the left half of Figure 4 (b). The optical tracking data captured for experiment B and for calibration were collected over a period of only approximately 30 min. each. Therefore, the motion of the walls during these periods was approximately 0.02 mm for the inside wall and 0.04 for the outside wall.

A sample data plot of the X and Y tracked paths is shown in Figure 5. The plot is of data collected from walking with the artifact in the vertical orientation (Figure 2b) during the second trial. Experiment B results are shown in Table 1 for the two trials including analyzed data from both the artifact bar length and angle between artifact end-markers. The root mean square deviation (RMSD) shows approximately 0.5 mm length difference from the actual 300 mm length and approximately 0.34° difference from 0° actual angle. The maximum error, 50th percentile, 95th percentile, and 99.7th percentile length and angle results are also shown.

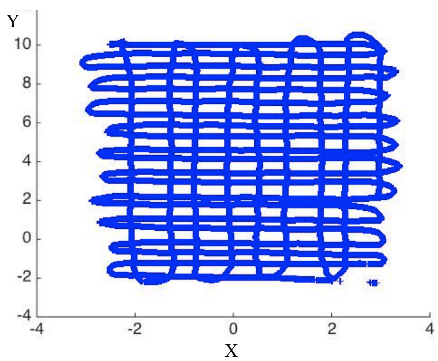


Figure 5. Sample data plot of the X and Y tracked paths of the artifact center.

LENGTH						
test	number of samples	RMSD , mm	Max, mm	50 percentile, mm	95 percentile, mm	99.7 percentile, mm
Length 1	86617	0.532	31.804	0.15	0.606	2.068
Length 2	84892	0.499	30.933	0.136	0.633	2.152
ANGLE						
test	number of samples	RMSD , deg.	Max, deg.	50 percentile, deg.	95 percentile, deg.	99.7 percentile, deg.
Angle 1	86311	0.349	28.545	0.262	0.565	1.305
Angle 2	84751	0.334	44.819	0.159	0.569	1.415

Table 1. Experimental results from the two trials.

The percentile error is listed in the ASTM E3064 standard, as opposed to the standard deviation, since the data distribution may not be Gaussian. Histogram plots of the 99.7th percentile distribution are shown in Figure 6. As shown, the length data is relatively evenly distributed whereas the angle data is shifted positive.

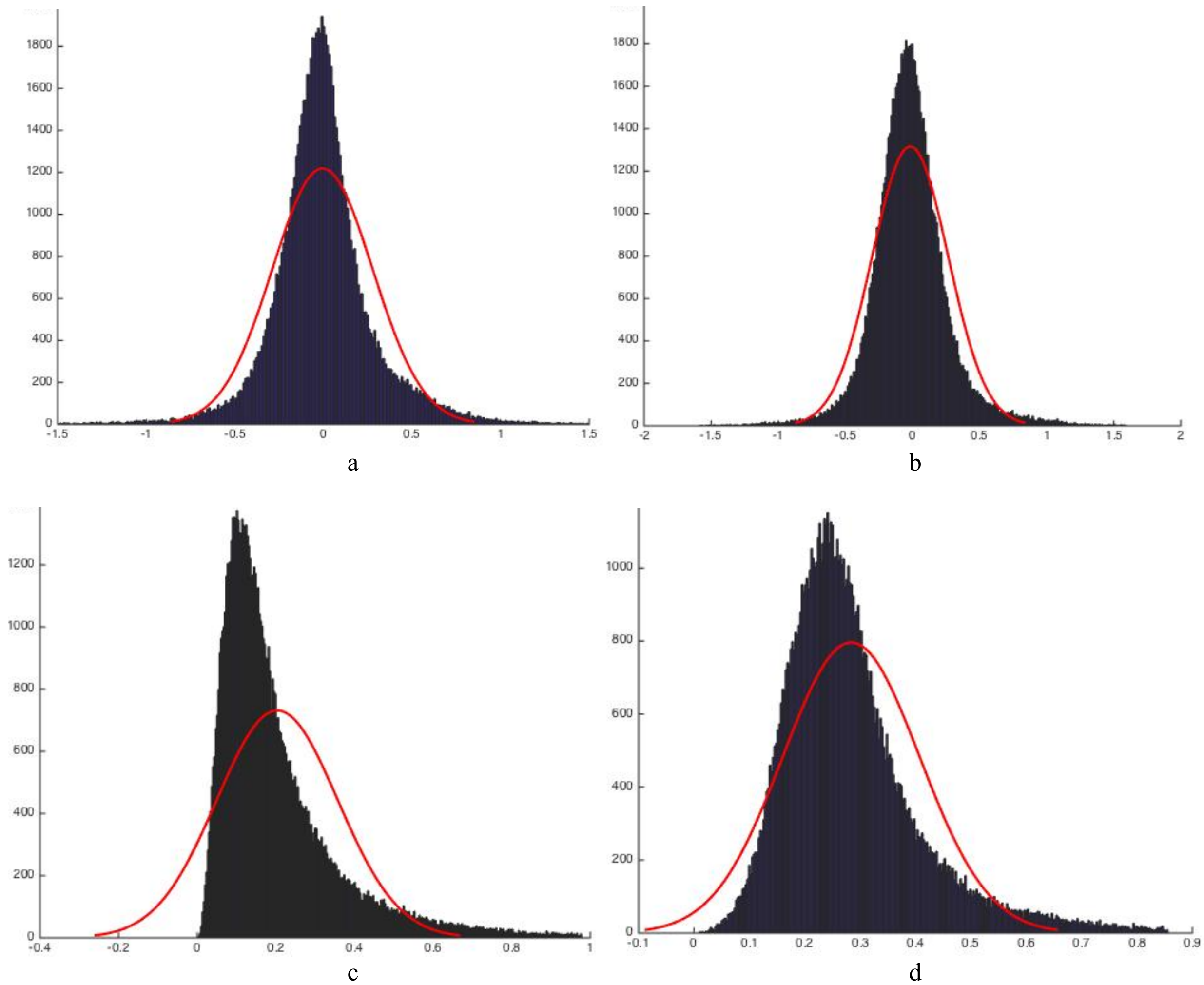


Figure 6. Histogram plots of the 99.7th percentile data shown in Table 1 for (a) Length from Trial 1, (b) Length from Trial 2, (c) Angle from Trial 1 and (d) Angle from Trial 2. The Gaussian distribution (red) is shown for comparison.

5 Conclusions

Optical tracking systems are used in a wide range of fields and have dramatically grown in market share over the past several years. As such, a team of optical tracking system manufacturers, users, and researchers who were part of an ASTM E57.02 task group developed a standard test method (ASTM E3064). Towards completion of the standard, the test method procedures within the standard were tested in two experiments described in this paper. The theoretical basis for data analysis was also described in this paper followed by analysis of the experimental data using this method. The paper verified the performance of an example 12 camera optical tracking system with an artifact, developed at NIST and measured previously using a coordinate measurement machine. Experimental results showed that the test method provides an RMSD of approximately 0.5 mm length difference from the actual 300 mm length and approximately 0.34° difference from 0° actual angle. Also, the use of percentiles versus standard deviation was verified through histogram plots resulting in offset from the mean. To ensure that the optical tracking system was mounted and calibrated properly, a high-accuracy laser tracker was used to verify that the system camera mounts only slightly moved (i.e., approximately 0.02 mm for the inside wall and 0.04 for the outside wall) relative to the artifact RMSD results. Additionally, a system calibration was performed prior to each experiment. Future optical tracking system standard efforts will be focused on system latency and perhaps other dynamic measurement performance characteristics.

Acknowledgements

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