Designation: E3064 – 16

Standard Test Method for Evaluating the Performance of Optical Tracking Systems that Measure Six Degrees of Freedom (6DOF) Pose[1]

This standard is issued under the fixed designation E3064; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 *Purpose*—This test method presents metrics and procedures for measuring, analyzing, and reporting the relative pose error of optical tracking systems that compute the pose (that is, position and orientation) of a rigid object while the object is moving.

1.2 *Usage*—System vendors may use this test method to determine the performance of their Six Degrees of Freedom (6 DOF) optical tracking system which measures pose. This test method also provides a uniform way to report the measurement errors and measurement capability of the system. System users may use this test method to verify that the system's performance is within the user's specific requirements and within the system's rated performance.

1.3 *Test Location*—The procedures defined in this standard shall be performed in a facility in which the environmental conditions are within the optical tracking system's rated conditions.

1.4 *Test Volume*—This standard shall be used for testing an optical tracking system working volumes of 3000 mm long by 2000 mm wide by 2000 mm high, 6000 mm long by 4000 mm wide by 2000 mm high, or 12 000 mm long by 8000 mm wide by 2000 mm high.

1.5 *Units*—The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E2919 Test Method for Evaluating the Performance of Systems that Measure Static, Six Degrees of Freedom (6DOF), Pose

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

2.2 *ASME Standard:*[3]

B89.4.19 Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems

2.3 *ISO/IEC Standards:*[4]

ISO/IEC Guide 99:2007 International Vocabulary of Metrology—Basic and General Concepts and Associated Terms (VIM: 2007)

ISO/IEC Guide 98–3:2008 Uncertainty of measurement—Part 3: Guide to the expression of uncertainty in measurement (GUM: 1995)

IEC 60050-300:2001 International Electro technical Vocabulary—Electrical and electronic measurements and measuring instruments

JCGM 200:2012 International Vocabulary of Metrology Basic and General Concepts and Associated Terms (VIM), 3rd edition

3. Terminology

3.1 *Definitions:*

3.1.1 *degrees of freedom, DOF, n*—any of the minimum number of translation or rotation components required to specify completely the pose of a rigid object. **E2919**

3.1.1.1 *Discussion*—

[1] This test method is under the jurisdiction of ASTM Committee E57 on 3D Imaging Systems and is the direct responsibility of Subcommittee E57.50 on Optical Tracking Systems.

Current edition approved June 1, 2016. Published June 2016. DOI: 10.1520/E3064-16

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Two Park Ave., New York, NY 10016-5990, http://www.asme.org.

[4] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

(1) In a 3D space, a rigid object can have at most 6DOF, three translations and three rotations.

(2) The term "degree of freedom" is also used with regard to statistical testing. It will be clear from the context in which it is used whether the term relates to a statistical test or the rotation/translation aspect of the object.

3.1.2 *measurement error, error of measurement, and error, n*—measured quantity value minus a reference quantity value. **(JCGM 200:2012)**

3.1.3 *metrology bar, n*—a rod of a known length having markers (active or passive) attached to both ends and used to estimate the errors of an optical tracking system.

3.1.4 *optical tracking system, n*—a tracking system that uses measurements obtained from camera images.

3.1.5 *pose, n*—a 6DOF vector whose components represent the position and orientation of a rigid object with respect to a coordinate frame. **E2919**

3.1.6 *precision, n*—the closeness of agreement between independent test results obtained under stipulated conditions. **E177**

3.1.7 *rated conditions, n*—manufacturer-specified limits on environmental, utility, and other conditions within which the manufacturer's performance specifications are guaranteed at the time of installation of the instrument. **ASME B89.4.19**

3.1.8 *reference system, n*—a measurement instrument or system used to generate a reference value or quantity. **E2919**

3.1.9 *relative pose, n*—change of an object's pose between two poses measured in the same coordinate frame. **E2919**

3.1.10 *repeatability, n*—precision under repeatability conditions. **E177**

3.1.11 *repeatability conditions, n*—conditions where independent test results are obtained with the same method on identical test items in the same laboratory by the same operator using the same equipment within short intervals of time. **E177**

3.1.12 *tracking system, n*—a system that is used for measuring the pose of moving objects and supplies the data as a timely ordered sequence.

3.1.13 *work volume, n*—a physical space, or region within a physical space, that defines the bounds within which a rigid object tracking system is acquiring data. **E2919**

4. Summary of Test Method

4.1 This test method provides a set of statistically based performance metrics and a test procedure to quantitatively evaluate the performance of an optical tracking system.

4.2 The measurement errors include the positional and orientation error components. Specifically, the test procedure measures the relative pose between two marker sets rigidly attached to the opposing ends of a fixed-length metrology bar as shown in Fig. 1. The relative pose is then decomposed into positional and angular components. Measurement errors are calculated from the positional and angular components as the artifact is moved about the work volume.

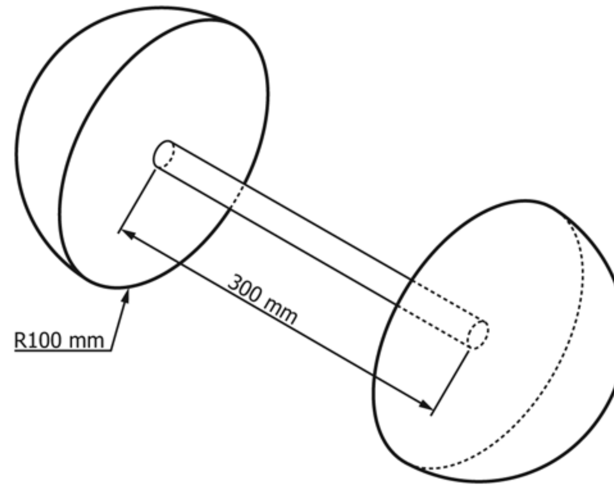

FIG. 1 Drawing of the artifact showing critical dimensions of the bar length and the maximum hemispherical volume inside which the markers can be placed.

5. Significance and Use

5.1 Optical tracking systems are used in a wide range of fields including: video gaming, filming, neuroscience, biomechanics, flight/medical/industrial training, simulation, robotics, and automotive applications.

5.2 This 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 of optical tracking systems.

5.3 Potential users often have difficulty comparing optical tracking systems because of the lack of standard performance metrics and test methods, and therefore must rely on the claims of a vendor regarding the system's performance, capabilities, and suitability for a particular application. This standard makes it possible for a user to assess and compare the performance of candidate optical tracking systems, and allows the user to determine if the measured performance results are within the specifications with regard to the application requirements.

6. Apparatus

6.1 *Artifact:*

6.1.1 A 300 mm long bar with markers rigidly attached to each end of the metrology bar shall be used as the 6DOF artifact. The bar shall have stiffness and thermal expansion characteristics such that the deflection is less than or equal to 0.01 mm. For example, the metrology bar shown in Fig. 2 satisfies these requirements.

6.1.2 A constant relative 6DOF pose is formed between the two clusters of markers located at the ends of the metrology bar. All markers shall be contained within hemispherical volumes with a maximum radius of 100 mm from the ends of the bar (see Fig. 1). Examples of metrology bars that can be used to evaluate optical tracking systems are shown in Fig. 2 (Ref (**1**))[5].

[5] The boldface numbers in parentheses refer to a list of references at the end of this standard.

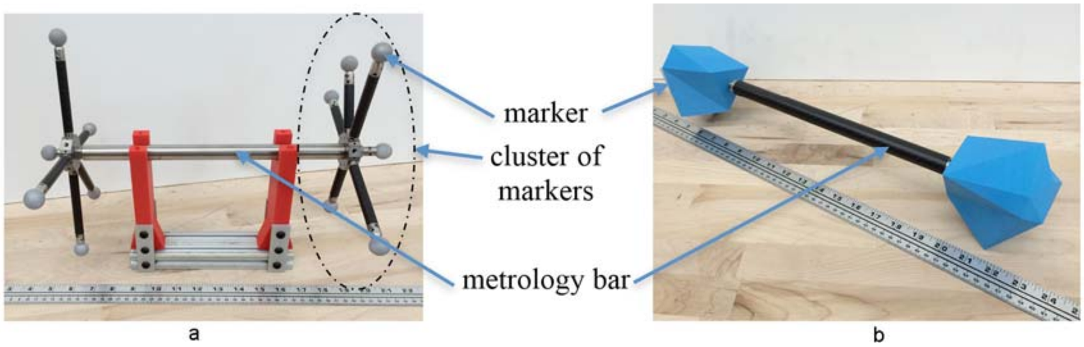

FIG. 2 Examples of artifacts for evaluating optical tracking systems having a 300 mm long metrology bar (a) with six passive, reflective markers, within 100 mm radius from the bar end, on each end, and (b) with a reduced pose ambiguity cuboctahedron, Ref (1), within 100 mm radius from the bar end, on each end.

7. Measurement Procedure

7.1 *Introduction:*

7.1.1 This section describes the basic procedure for determining the pose measurement error of an optical tracking system.

7.2 *Pose Measurement:*

7.2.1 The *X* and *Y* axes are aligned with the work volume in the horizontal plane as shown in Fig. 3, and *Z* is aligned with the vertical axis. Move the metrology bar throughout the work volume along two regular patterns: (*X* pattern) parallel, straight line segments back-and-forth along the *X* axis with the paths separated by at most, the metrology bar length as shown in Fig. 3 (a) and (*Y* pattern) parallel, straight line segments back-and-forth along the *Y* axis with the paths separated by at most, the metrology bar length as shown in Fig. 3 (b). The distance between the boundary lines and the limits of the work volume shall be at most, one-half of the metrology bar length. The center of the metrology bar shall traverse the *X* pattern followed by the *Y* pattern with artifact orientation #1 as shown in Fig. 3 (c) in a continuous smooth motion. This traversal shall be repeated two more times, once with artifact orientation #2 and once with artifact orientation #3. The data from all three traversals shall be combined into a single data set.

7.2.2 The metrology bar paths and orientations shall be chosen as described in 7.2.1. The height of the centroid of the metrology bar shall remain approximately 1000 mm above the bottom of the test volume.

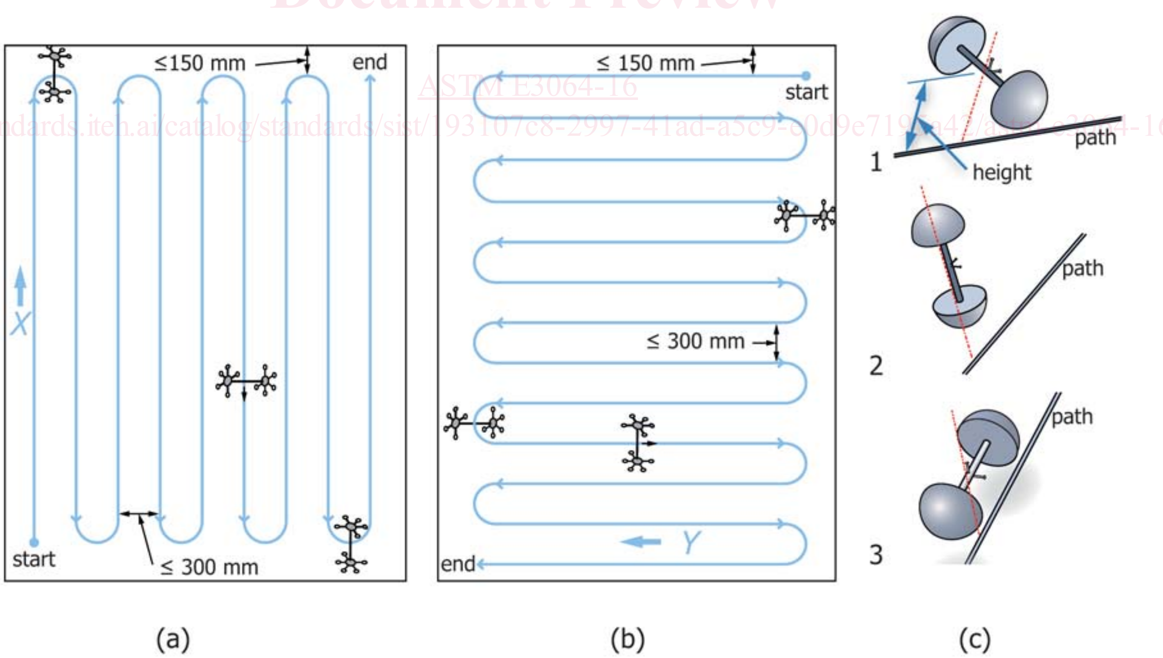

FIG. 3 The (a) *X* pattern and (b) *Y* pattern are combined to make a single path along which the metrology bar is moved throughout the work volume. (c) Artifact (shown with axes on bar center) orientations with respect to the path: 1) perpendicular to the path segments in the plane of motion, 2) perpendicular to the path segments and normal to the plane of motion, and 3) in-line with the path segments in the plane of motion.

NOTE 1—Example artifact shown in (a) and (b) is oriented with respect to the path as in 1) perpendicular to the path segments in the plane of motion.

7.2.3 The centroid of the metrology bar shall be moved at a relatively constant walking speed of 1200 ± 700 mm/s.

8. Pose Measurement Error

8.1 This section describes methods for computing pose measurement errors of an optical tracking system (OTS) using the artifact. For each instance of time t, the optical tracking system measures the pose of an object as:

$$_{OTS}\hat{H}_{Object}(t) = \begin{bmatrix} _{OTS}\hat{R}_{Object}(t) & _{OTS}\hat{T}_{Object}(t) \\ 0 & 1 \end{bmatrix} \quad (1)$$

Here, $_{OTS}\hat{R}_{Object}(t)$ is a 3 × 3 matrix describing the orientation of the object and $_{OTS}\hat{T}_{Object}(t)$ is a 3-dimensional vector describing the position of the object in the optical tracking system coordinate frame. In our artifact, two objects are considered corresponding to the left and right ends of the metrology bar. The optical tracking system measures the poses of the left and right ends, and the corresponding 4 × 4 matrices are defined respectively as:

$$_{OTS}\hat{H}_{Left}(t) = \begin{bmatrix} \hat{R}_{Left}(t) & \hat{T}_{Left}(t) \\ 0 & 1 \end{bmatrix} \text{ and} \quad (2)$$

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

Because the bar is rigid, the relative pose between the left object and the right object is constant in time (see Fig. 4) and can be defined as:

$$\begin{aligned} _{Left}\hat{H}_{Right}(t) &= {_{OTS}\hat{H}^{-1}_{Left}}\ {_{OTS}\hat{H}_{Right}} \\ &= \begin{bmatrix} \hat{R}_{Left}(t) & \hat{T}_{Left}(t) \\ 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} \hat{R}_{Right}(t) & \hat{T}_{Right}(t) \\ 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} \hat{R}(t) & \hat{T}(t) \\ 0 & 1 \end{bmatrix} \end{aligned} \quad (3)$$

The angle of rotation is calculated as:

$$\hat{\theta}(t) = 2 * \operatorname{asin}\left(\sqrt{\hat{q}_x^2(t)+\hat{q}_y^2(t)+\hat{q}_z^2(t)}\right) \quad (4)$$

Here, $(\hat{q}_w(t),\hat{q}_x(t),\hat{q}_y(t),\hat{q}_z(t))^T$ is the unit quaternion representation of $\hat{R}(t)$, Ref **(2)**, where $\hat{q}_w(t)$ is the scalar component of the quaternion.

8.1.1 A reference system measurement is used to measure the relative pose between two groups of markers. The reference system measurement shall have an uncertainty that is at least ten times smaller than the uncertainty of the optical tracking system under test. The relative pose between the left object and right object at the ends of the metrology bar is measured by the reference system measurement as:

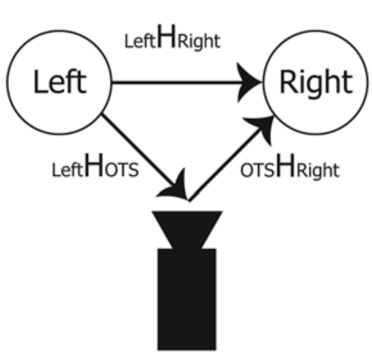

FIG. 4 Transformation between the Left Object and the Right Object

$$_{Left}H_{Right} = \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} I & T \\ 0 & 1 \end{bmatrix} \quad (5)$$

The coordinate frames associated with the right and left ends of the bar are rotationally aligned using the reference system. Where $R=I$, and I is the identity matrix.

8.1.2 The following sections describe two methods for evaluating the optical tracking system. In 8.2, measurements are taken relative to the measured relative pose of a test artifact, which is measured by a more accurate system, and in 8.3 the measurements are taken relative to the mean value of the collected data.

8.2 *Error Statistics using a Reference System:*

8.2.1 This section describes the computation of system error statistics relative to a precisely characterized test artifact, such as the one described in Section 6.

8.2.2 The relative measured pose $_{Left}\hat{H}_{Right}(t)$ (see Eq 3) at time t can be compared to the reference system measured pose $_{Left}H_{Right}$ (see Eq 5). Specifically, the positional error at time t can be calculated as:

$$e_{p(t)} = \|\hat{T}(t)\|_2 - \|T\|_2 \quad (6)$$

and the orientation error at time t can be calculated as:

$$e_{o(t)} = \hat{\theta}(t) - 0 = \hat{\theta}(t) \quad (7)$$

where $\hat{\theta}(t)$ is calculated using Eq 4 and $\| \ \|_2$ denotes the 2-norm of the vector.

8.2.3 The statistics on these errors include: the root mean square error, the maximum error, and the percentile error. The root mean square error is calculated as:

$$\text{Root Mean Square Error} = \sqrt{\frac{1}{N}\sum_{t=1}^{N} e_t^2} \quad (8)$$

The maximum of the errors is defined as:

$$e_{\max} = \max(|e_1|,|e_2|,...|e_N|) \quad (9)$$

Here, e_t is the (positional or orientation) error at time t, and N is the number of data samples collected.

8.2.4 A method for estimating the percentile error of a data set is described in Ref **(3)**. For a series of errors $\{|e_1|,|e_2|,...,|e_N|\}$, a new ordered set $\{E_1, E_2, ..., E_N\}$ is constructed where the errors are ordered by increasing value. The percentile error of the data can be estimated from N measurements as follows: for the pth percentile, set $\frac{p}{100}(N + 1)$ equal to $k+d$ for k, an integer, and d, a fraction greater than or equal to 0 and less than 1. The estimated error percentile $E(p)$ is defined as follows:

$$E(p) = \begin{cases} E_k + d(E_{k+1} - E_k) & 0<k<N \\ E_1, & k = 0 \\ E_N, & k \geq N \end{cases} \quad (10)$$

In this standard, $E(99.7)$, $E(95)$ and $E(50)$ shall be reported.

8.3 *Repeatability without Reference System Measurement:*

8.3.1 This section describes the computation of system repeatability statistics using a test artifact not measured by a reference system. The system repeatability statistics are computed from the measurements of the collected data rather than