NIST Interagency Report
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NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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## Abstract

The ASTM E2919-22 standard provides a test method for evaluating 3D imaging systems for static pose. This standard was developed in conjunction with industry and NIST led the effort. The standard was initially published in 2014. The standard was revised in 2022 and the Intelligent Systems Division at NIST led that effort. This report introduces methods to calculate orientation and uncertainty from 3D point cloud data of physical artifacts.

## Keywords

Static pose; Orientation; Orientation uncertainty; 3D point cloud.

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## Acknowledgments

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## 1. Introduction

The ASTM E2919-22[i] standard provides a test method for evaluating 3D imaging systems for static pose estimation of an object. The standard was originally developed in conjunction with industry and NIST led the effort. The standard was initially published in 2014. This standard underwent a revision and was re-published in 2022. The Intelligent Systems Division at NIST also led that effort.

Object poses as measured by 3D imaging systems are derived from the 3D point cloud measurements from these systems, and the pose measurement uncertainty may not be specified by the manufacturer. To ensure that the data from different 3D imaging systems are processed identically, the new appendix in the ASTM E2919-22 considers the use of a common algorithm to determine the orientation and uncertainty from 3D point cloud data of an artifact. This document briefly describes the algorithm, and the software implementation is provided as MATLAB and Python code. The software download includes some sample data sets and a script to demonstrate the implementations.

## 2. Software Specifications

| | |
|---|---|
| **NIST Operating Unit(s)** | Engineering Laboratory, Intelligent Systems Division |
| **Category** | Orientation Uncertainty and Orientation Uncertainty Estimation |
| **Targeted Users** | Users of 3D imaging systems, manufacturers, and software vendors |
| **Operating System(s)** | Tested on Windows 10 64-bit version, but the code may work on any operating system supported by MATLAB and Python with the appropriate dependencies listed below. |
| **Programming Language** | 1) MATLAB R2023b<br>2) Python 3.9.12 with NumPy, SciPy, and MatPlotLib modules |
| **Inputs/Outputs** | **Input:** Segmented 3D data of a non-symmetric artifact<br>**Output:** Orientation and uncertainty |
| **Documentation** | Source code and test data can be downloaded using the link below:<br>https://github.com/usnistgov/ASTM_E2919_22_Pose |
| **Accessibility** | N/A |
| **Disclaimer** | https://www.nist.gov/director/licensing |

## 3. Description of the Algorithm

The procedure to calculate the orientation and uncertainty are described below.

1. Collect 3D point clouds $\boldsymbol{P}_m$ , m= 1,…,M, (M >= 200) from the 3D imaging system under the same experimental conditions (i.e., the same artifact, sensor position, lighting conditions, etc.). Make sure individual datasets are statistically equivalent to each other. For example:
    a. The number of points N in each dataset is almost the same, such that the range of the values between the datasets do not exceed 0.5% of the mean value of the number of points in each dataset. For example, if the mean number of points in the M datasets are 8000, then the acceptable minimum and maximum number of points in each dataset is 7980 and 8020 respectively.

b. The extreme values of the coordinates of 3D points (X,Y,Z) should also be within ±0.5% interval. For example, if the mean for $X_{min}$ in M datasets is $\widehat{X_{min}}$= 100 mm, then $X_{min}$ in each m[th] dataset should be between 99.5 mm and 100.5 mm. The same should apply for $X_{max}$ and for Y and Z coordinates.
c. There are no large gaps (missing points) in the acquired datasets. The number of missing points on a surface of measured object should be a small fraction of points captured from the surface, i.e., the fraction < 0.5 %.

2. For each m-th dataset, m=1,…,M, calculate the 3x3 covariance matrix $\boldsymbol{C}_m$.
3. Perform a Singular Value Decomposition (SVD) of each $\boldsymbol{C}_m$

$$(\boldsymbol{R}_m, \boldsymbol{S}_m, \boldsymbol{R}_m) = svd(\boldsymbol{C}_m) \tag{1}$$

Matrix $\boldsymbol{R}_m$ is a 3x3 rotation matrix defining the orientation of point cloud $\boldsymbol{P}_m$. It is important that the scanned artifact is not symmetric (such as a sphere or a square planar target) so that eigenvectors for different datasets are uniquely identifiable.

4. Calculate the mean rotation matrix $\overline{\boldsymbol{R}}$ from all M matrices $\boldsymbol{R}_m$ as described in [ii]. The method is described below:
   **a.** Calculate $\boldsymbol{R}_{sum}$ from *M* instantaneous rotation matrices $\boldsymbol{R}_m$, $m = 1, \dots M$ as

$$\boldsymbol{R}_{sum} = {}^{1}\!/_{M} \sum_{m=1}^{M} \boldsymbol{R}_m \tag{2a}$$

   Note that in most real situations $\boldsymbol{R}_{sum}$ is not a rotation matrix as its columns are not orthonormal (since repeated *M* measurements are affected by noise).
   **b.** Calculate $\boldsymbol{R}_c$ as

$$\boldsymbol{R}_c = \boldsymbol{R}'_{sum}\,\boldsymbol{R}_{sum} \tag{2b}$$

   c. Perform Singular Value Decomposition on $\boldsymbol{R}_c$

$$(\boldsymbol{U}, \boldsymbol{D}, \boldsymbol{V}) = svd(\boldsymbol{R}_c) \tag{2c}$$

   All three matrices $(\boldsymbol{U}, \boldsymbol{D}, \boldsymbol{V})$ are 3x3 and $\boldsymbol{D}$ is diagonal (i.e., $D_{i,j} = 0$ for $i \neq j$ And $D_{i,i} > 0$ for $i, j = 1,2,3$).
   d. Calculate another 3x3 diagonal matrix $\boldsymbol{\Lambda}$ such that

$$\Lambda_{i,i} = {}^{1}\!\big/_{\sqrt{D_{i,i}}} \tag{2d}$$

   e. Calculate the mean rotation matrix $\overline{\boldsymbol{R}}$ as

$$\overline{\boldsymbol{R}} = \boldsymbol{R}_{sum}\,\boldsymbol{U}\,\boldsymbol{\Lambda}\,\boldsymbol{U}'\ . \tag{2e}$$

**5.** For each dataset m, calculate a small rotation matrix $\Delta\boldsymbol{R}_m$ which is the deviation of $\boldsymbol{R}_m$ from the average rotation $\overline{\boldsymbol{R}}$

$$\Delta\boldsymbol{R}_m = \overline{\boldsymbol{R}}\,\boldsymbol{R}'_m \tag{3}$$

   where $\boldsymbol{R}'_m$ is the transpose of matrix $\boldsymbol{R}_m$.

6. Calculate the small angle of rotation $\alpha_m$ for each $\Delta\boldsymbol{R}_m$ as

$$\alpha_m = arccos\left(\frac{1}{2}\left(trace(\Delta\boldsymbol{R}_m) - 1\right)\right) \tag{4}$$

7. The uncertainty in the orientation is obtained by conducting 200 measurements and obtaining the 95th percentile of the values of $\alpha_m$. Note that the distribution of the values of $\alpha_m$ is not symmetrical and non-Gaussian.

## 4. Implementation of the Algorithm

The software code was developed using two different software suites, namely, MATLAB and Python. The corresponding versions and dependent toolboxes/packages/modules are listed in the software specifications (Sec. 2). This software code may work in other versions of these suites and other operating systems where these suites are available, but compatibility is not guaranteed.

Slight differences between the results of these implementations could be attributed to the implementation of the SVD routine in these software suites, the discussion of which is beyond the scope of this report.

## 5. Testing and Validation

The software described in this report was developed and tested using Windows 10 (Enterprise, 64-bit version) and requires MATLAB R2023b, and Numpy, Scipy, Glob, and MatPlotLib modules for Python 3.9.12 (as part of the Anaconda distribution). These dependencies are currently available on Windows, Mac, and Linux for all three suites, but the code was tested only on Windows 10 (Enterprise 64-bit).

The software was tested on over 250 segmented datasets of a non-symmetric artifact. The picture of the artifact and a view of its 3D imaging data are shown in Figure 1 and Figure 2, respectively. The original data was from a structured-light sensor and 250 datasets were generated by segmenting the object data from its background mounting apparatus. The artifact was supported during scanning in such a way that there is about 200 mm separation between the artifact and its nearest scannable surface. This was done to simplify the segmentation process.

Figure 1: Picture of the artifact used in this work

Figure 2: Truncated 3D data of the artifact

The segmentation was initially done manually on one dataset using CloudCompare software and that first segmented dataset was used as a template to segment the rest of the files using

MATLAB automatically. The segmented data was visually inspected to ensure that data points that did not belong to the artifact were excluded in the pose calculation and its uncertainty. In all the instances, the software performed without any errors.

The software does not perform any input validation; however, poseAlgo1.m and poseAlgo1.py demonstrate application of the software using delimited text files of 3D imaging data. For the artifact data provided with this software, the angles (calculated using equation 4) ranged from 0.125 milliradians to 3.438 milliradians, with the 95$^{th}$ percentile value of 2.204 milliradians (see Figure 3).

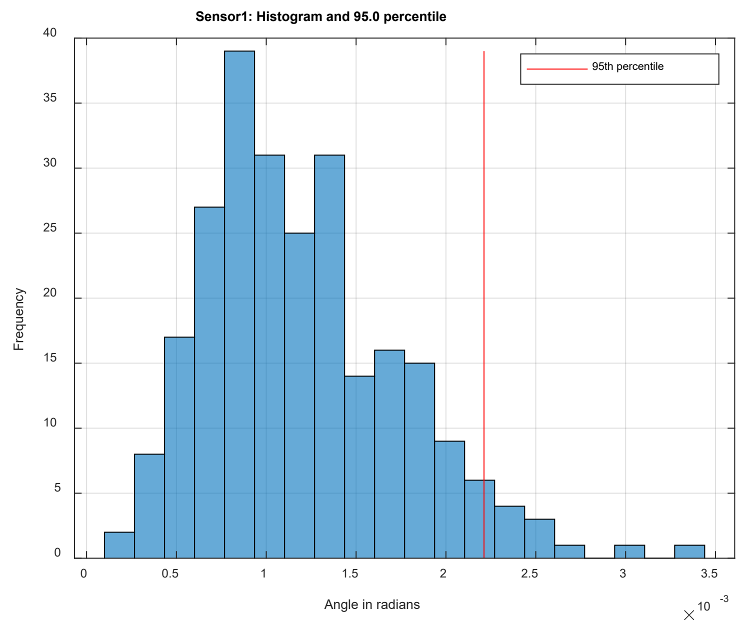


Figure 3: Histogram of the angles ($\alpha_m$) as calculated using equation 4

## 6. Summary

This document describes an algorithm to determine the orientation and its uncertainty as mandated in the ASTM E2919-22 standard. It is implemented using two software suites, tested on multiple datasets, and is provided as a download. Results are provided for one artifact, where the 95$^{th}$ percentile value of the angles ($\alpha_m$) was 2.204 milliradians. This uncertainty calculation can also be used to select a reference method (including the reference instrument) whose orientation measurement uncertainty needs to be ¼ times the maximum possible error (MPE) of the orientation measured by the system under test[1].

[1] Note that it is an industry practice is to use a 4:1 ratio of MPE to expanded uncertainty. The ratio of 4:1 is called a simple acceptance/rejection decision rule per ASME B89.7.3.1, test uncertainty ratio per ANSI/NCSLI Z540.3:2006 (and subsequently ISO 17025) or measurement capability index per JCGM 106:2012.

## 7. References

[1] ASTM (2022). ASTM E2919-22, Standard Test Method for Evaluating the Performance of Systems that Measure Static, Six Degrees of Freedom (6DOF), Pose, ASTM International, West Conshohocken, PA, 2023, www.astm.org.

[2] *M. Moakher, "Means and averaging in the group of rotations," SIAM Journal on matrix analysis and applications, pp. 1–16, 2002*

## Appendix A. Supplemental Materials

The software code and data files are available at https://github.com/usnistgov/ASTM_E2919_22_Pose