Dimensional measurement traceability of 3D imaging data

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ABSTRACT

This paper discusses the concept of metrological traceability to the International System of Units (SI) unit of length, the meter. We describe how metrological traceability is realized, give a recent example of the standardization of laser trackers, and discuss progress and challenges to the traceability of 3D imaging data.

Keywords: traceability, calibration, dimensional metrology, simulation, laser scanning, laser tracker

1 INTRODUCTION

Non-contact optical measurement technology for dimensional metrology is advancing rapidly. The data rate for acquiring point coordinates is many orders of magnitude faster than traditional contact measurement techniques, often with reduced labor costs. Consequently, modern manufacturing is rapidly adopting these methods for a variety of metrological needs including workpiece accept/reject decisions, process control, reverse engineering and product development.

To be useful for dimensional metrology applications, measurement systems must be calibrated with respect to the internationally accepted unit of length—the meter[ii]. Additionally, a statement regarding the accuracy of the measurement system is essential to the correct instrument selection for each measurement situation. Fortunately, over a century[iii] of dimensional metrology has institutionalized both the hierarchical chain of length standards and the evaluation of measurement accuracy. Over the past few decades the impact of measurement accuracy (more correctly referred to as measurement uncertainty) has become increasingly important as mechanical assemblies (aircraft, automobiles, etc.) now include large numbers of high accuracy components from both different factories and different nations. Consequently, efforts are currently underway to quantify new 3D optical measurement systems in a manner that integrates them into the dimensional metrology community.

2 METROLOGICAL TRACEABILITY

2.1 Concepts of metrological traceability

To facilitate the widespread acceptance of 3D imaging technology, dimensional metrologists require knowledge of the accuracy of the measurement results and the ability to demonstrate their connection back to the SI unit of length, i.e. the meter. This informational path is known as metrological traceability. The International Vocabulary of Metrology [1] defines metrological traceability as a "property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty." Hence, metrological traceability involves both an uncertainty evaluation of a measurement result and explicit evidence of the connection to the meter. Uncertainty evaluations are now standardized using the procedures of the *Guide to the Evaluation of Uncertainty in Measurement* (GUM), which is both an International Guide and a US National Standard (NCSL Z540-2) [2].

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[ii] US customary units based on inches are defined in terms of, and realized by, the meter; 1 inch = 0.0254 meter exactly.
[iii] In 1875 the "treaty of the meter" signed by 17 nations, including the US, established the meter as an international unit of length.

Metrological traceability is defined as a property of a measurement result. Hence, organizations, individuals, or instruments are not themselves traceable. Indeed, traceability is a special property of a measurement, and many measurements do not have explicit metrological traceability. By explicit traceability, we mean the ability to produce the appropriate documents and uncertainty evaluations to satisfy a request to demonstrate traceability, for example from an auditor. In the particular case of instrument calibrations, it is widely recognized that these procedures should yield metrological traceability. Specifically, International Standard ISO 17025 *General Requirements for the Competence of Testing and Calibration Laboratories* [3], which is used for laboratory accreditation, requires calibration laboratories to demonstrate the metrological traceability of their calibration results. The process of obtaining traceable calibration results requires both a traceable reference standard(s) from which the connection to the meter arises and the evaluation of the measurement uncertainty of the calibrated values.

The conceptual underpinnings of metrological traceability are straightforward. The requirement for the explicit connection to the meter ensures that all measurements are based on a common unit of length. Without a common standard of length, it would be impossible to achieve interchangeable components among different manufacturers, and modern manufacturing, technology, and science would be impossible as well. Alongside traceability, requiring an uncertainty statement (which describes the accuracy and confidence of the measurement result) ensures the appropriate use of the measurement. It would be hopeless to inspect components that have a manufacturing (i.e. blueprint) tolerance of 0.1 mm with a measurement system yielding 1 mm uncertainty. It would be disastrous if such a system was used believing that the measurement system was accurate and resulting in numerous erroneous inspection decisions. This is the metrological equivalent of losing control of the unit of length.

The connection between a measuring instrument's calibration procedure and its metrological traceability is fundamental. For most industrial measurements that require metrological traceability, the uncertainty evaluation contains a term, associated with the instrument's performance[iv], which is derived from the calibration report. If a calibration report for the specific instrument in use is not available, then the manufacturer's specifications are typically employed, as they represent an upper bound on the performance results of the calibration procedure. In either case, it is essential that the calibration procedure be sensitive to any significant error sources attributable to the instrument that could be manifested in the measurement under consideration. If the calibration procedure omits the assessment of a significant error in the instrument, then the uncertainty associated with the instrument's measurement result cannot be evaluated[v], and its magnitude is potentially unlimited. This emphasizes the importance of well-designed calibration procedures, and correspondingly, the need for careful deliberation by standardization committees that are responsible for developing many of the testing procedures that result in commercial instrument specifications.

2.2 Elements of metrological traceability

ASME B89.7.5 *Metrological Traceability of Dimensional Measurement Results to the SI Unit of Length* [4], provides guidance to demonstrate metrological traceability for industrial dimensional measurements. The basic requirements of dimensional measurement traceability via B89.7.5 consist of six steps:

1. A clear statement of the quantity under measurement, i.e., the measurand.
2. Identification of the measurement system and standards used in the measurement.
3. A GUM compliant statement of uncertainty for each measurement result.
4. An uncertainty budget that describes and quantifies the significant uncertainty contributors.
5. Documentation traceability of the length standards used in the measurement back to an appropriate metrological terminus.
6. A measurement assurance program to ensure the condition of the measurement system and standards used in the measurement.

In step one, the *measurand* specifies the particular quantity that is subject to measurement. It is defined by a set of specifications, i.e., instructions, that specifies what we intend to measure; it is not a numerical value. A well specified measurand provides enough information, and is generic enough, to allow different techniques to be used to perform the

[iv] The performance specifications are usually reported under a set of constrained environmental conditions under which the calibration was conducted. If the industrial conditions of measurement differ significantly, then appropriate adjustments to the uncertainty arising from the instrument are needed.

[v] Or is incorrectly evaluated due to the omission of a significant uncertainty source.

measurement and get the same result. The more completely defined the measurand, the less uncertainty will (potentially) be associated with its realization. A completely specified definition of the measurand has associated with it a unique value and an incompletely specified measurand may have many values, each conforming to the (incompletely defined) measurand, i.e., there is no unique answer to an ambiguously defined measurand.

Step two is both simple and has long been a part of any traceability claim. In particular, step two involves explicitly stating the measurement system or calibrated standards which are part of the traceability chain back to the meter.

Steps three and four represent a significant increase in the rigor of industrial traceability and reflects the modern thinking that a GUM uncertainty evaluation is integral to measurement traceability. Well established industrial practices, such as the evaluation of measurement variation alone, are insufficient to assert traceability. For example, repeated measurements of a set of uncalibrated workpieces, often called gauge repeatability and reproducibility (GR&R) are required to be supplemented with measurements of calibrated artifacts (or calibrated workpieces) to assess the measurement bias. Similarly, B89.7.5 recognizes that other forms of GUM compliant evaluations may be employed, such as Monte Carlo simulation. This is particularly effective for addressing measurands that are defined though complex datum reference frames, as is commonly the case for mechanical components.

Step five requires “documentation traceability”, i.e., calibration reports or other explicit evidence of a connection back to the definition of the meter. This documentation should exist for the primary length standards used in the measurement. This step is customized for industrial dimensional measurements by limiting the documentation to only the primary length based quantities. Hence, B89.7.5 minimizes the amount of paperwork associated with a traceability claim.

Additionally, B89.7.5 specifically requires that the documentation traceability arises from an appropriate metrological terminus; this could be one of:

1. A calibration report from a National Measurement Institute (NMI).
2. A calibration report from a competent laboratory that satisfies section 5.6 (entitled measurement traceability) of ISO 17025 or section 9 of NCSL Z540-1.
3. A realization of the meter, e.g. certain spectral lamps or laser wavelengths, together with evidence that realization can be achieved at the claimed level of uncertainty.

We point out that the most common terminus, a calibration report, is only required to have metrological competence, not necessarily laboratory accreditation. This is appropriate, since it recognizes that many industrial measurements are highly product specific and hence involve gauges or instruments that may be unique to that facility. B89.7.5 does recognize laboratory accreditation as a de facto means to demonstrate competence. We also note that although documentation traceability is required only for the primary length standards, the required GUM uncertainty evaluation implicitly provides a connection to the SI units for all uncertainty sources (except for dimensionless quantities), otherwise it would be not be possible to evaluate each standard uncertainty.

Finally, step six ensures that reasonable due diligence is taken for the measurement assurance. This includes periodic calibrations of artifact standards and measurement instruments and that the measurement systems are operating within their rated conditions.

We now address how these six steps are realized for measurements made with 3D coordinate metrology instrumentation. A modern approach for such metrological traceability starts with a calibration procedure that quantifies all the significant error sources inherent in the instrument. This procedure is executed using some form of calibrated artifact or standard length. It is this calibrated standard that supplies the connection to the meter, and its calibration certificate (from a competent laboratory) provides the explicit “documentation traceability” required in ASME B89.7.5.

Evaluating the GUM compliant uncertainty for a measurement result using 3D coordinate metrology instrumentation involves a few steps. First, uncertainties of the individual point coordinates of a specific 3D measurement scan are obtained. This is done by using the instrument calibration results, together with information regarding the environmental conditions, operator effects, and other factors and combining them in a GUM compliant uncertainty evaluation. Once the uncertainties of the individual points have been evaluated, this information can be combined with the individual point coordinates themselves and propagated into a useful measurement quantity, e.g., the diameter of a cylinder.

Frequently this propagation is obtained through Monte Carlo simulation [5]. Each Monte Carlo simulation cycle draws a set of individual point coordinates and computes, using a fitting algorithm, the measurement result of interest—a cylinder diameter in the above example. This process is repeated for a large number of cycles where each set of point coordinates differs slightly due to the uncertainties of the individual points. The collection of computed results (e.g. cylinder diameters) is statistically evaluated to yield a GUM-compliant uncertainty statement for this measurement feature. One of the advantages of the simulation technique is its ability to capture complicated relationships between the number and location of the measurement points and the corresponding uncertainty in the desired feature. For example, the uncertainty associated with a cylinder diameter can be orders of magnitude larger than that of the individual points if the points are confined to only a small portion of the arc of the cylinder. Alternatively, there are other cases where the uncertainty of the measured diameter is significantly less than that of the individual points.

3 STANDARDIZATION OF LASER TRACKERS

One recent example of obtaining metrological traceability is provided by ASME B89.4.19 *Performance Evaluation of Laser Based Spherical Coordinate Measurement Systems*, used to evaluate laser tracker systems. Laser trackers are spherical coordinate measurement instruments that optically measure the distance to a cooperative target, usually a spherically mounted retroreflector (SMR). The ASME standard describes the calibration procedure used to quantify errors associated with the opto-mechanical design of a laser tracker instrument. A schematic of a laser tracker design is shown in Figure 1.

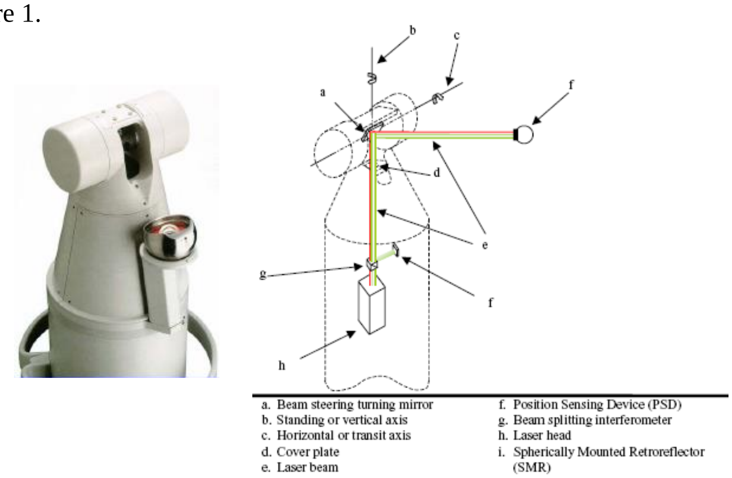

Figure 1: A schematic of the opto-mechanical construction of a laser tracker

The objective of the B89.4.19 standard is to provide a reasonable[vi] series of tests to quantify the significant error sources of the all common commercially available laser trackers and to provide metrological traceability of the results. As an example of examining the sensitivity of the calibration procedure to various error sources, we consider Figure 2, which shows the effect of a squareness error between two nominally orthogonal axes, such as the horizontal and vertical axes on a laser tracker. From the figure it is clear that the measurement of a calibrated reference length oriented either horizontally or vertically (denoted as X and Y in the Figure 2) is completely insensitive to this error source. However, selecting the orientation of the calibrated reference length along the axis diagonal reveals the squareness error as a measured length error[vii]. Figure 2 also shows one of the required testing positions that involves determining the distance between two SMR seats that are oriented on a diagonal with respect to the laser tracker's axis system; this effectively captures the squareness error source of the tracker under test.

The B89.4.19 standard includes two categories of testing. Firstly, the ranging technology of the tracker is tested in a long 1D range against a laser interferometer that has been connected to the meter by its calibration against the iodine

[vi] Creating a reasonable testing procedure is always a balance between the extensiveness of the metrological testing and the time and cost of the procedure.

[vii] In metrology, an error is a signed quantity defined as the measured value minus the true value. In the B89.4.19 Standard, the true value is estimated as the calibrated value of the reference length.

stabilized laser[viii]. This procedure connects the tracker's ranging technology to the meter, and the results of the test (i.e. the reported errors) establish the uncertainty of this connection. Secondly, the volumetric performance of the tracker is tested through a series of measurements of calibrated reference lengths located and oriented in a manner sensitive to known error sources associated with commercial tracker designs. Figure 2 shows an example of one such reference length orientation.

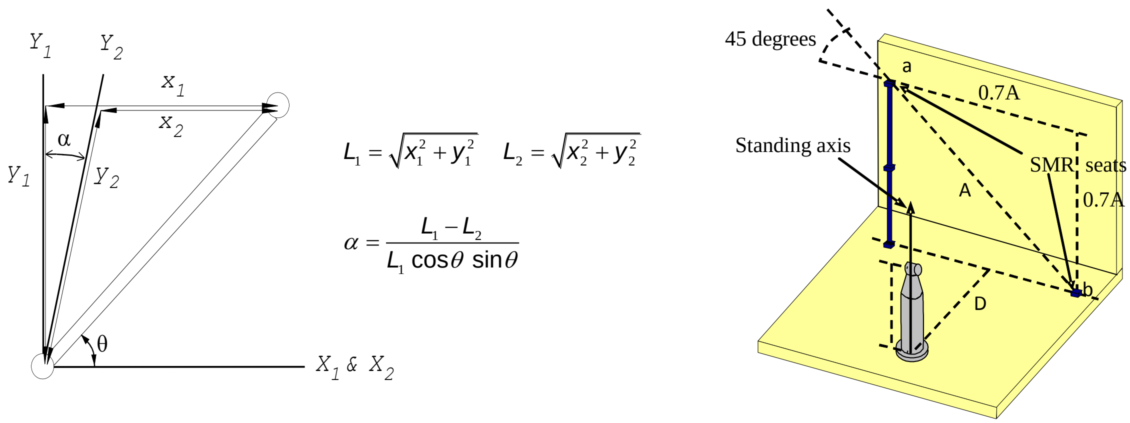

Figure 2: (left) diagram showing the effect of an axis squareness error; (right) one of the testing positions in the ASME B89.4.19 standard to detect this error source.

The results of the B89.4.19 testing are metrologically traceable because the normative Appendix A of the standard describes the requirements for the reference lengths used in the testing procedure. In particular, documentation traceability (see section 2.2) of the reference lengths used in the testing procedure is required. Furthermore, the uncertainty of the reference length at the time the B89.4.19 measurements are performed is also required. This uncertainty includes not only that of the reference length, as described on its calibration report, but also all significant uncertainty sources affecting the reference length at the time the measurement is performed. Consequently, the requirements of B89.4.19 Appendix A provide metrological traceability for the test results of the Standard. Furthermore, these test results (whether reported as specific test values or reported simply as the tracker being within the manufacturer's specifications) form the basis of the instrument's contribution to the uncertainty of subsequent measurements (e.g., on manufactured workpieces), and hence the connection of those measurements to the meter. Informative Appendix B of the Standard provides additional discussion of the procedure for workpiece measurements that require metrological traceability via a laser tracker that has undergone B89.4.19 testing.

4 PROGRESS ON LASER SCANNING: STANDARDIZATION AND TRACEABILITY

Recently, the ASTM E57 committee on 3D Imaging Systems [6] has been actively working on developing calibration procedures for laser scanners and other optical measurement instrumentation that involve non-cooperative targets (i.e. the passive reflectance from the surface under measurement). This work, together with concomitant research in GUM uncertainty sources associated with optical measurements will form the foundation for metrological traceability of 3D imaging systems used for dimensional measurements.

This activity has many complicating factors. For example, 3D imaging systems are available in a wide variety of designs including stationary systems, hand held devices, as probes used with other measurement systems (e.g. coordinate measuring machines), and as spherical coordinate measurement systems (similar to trackers but with many more design variations). Additionally the use of non-cooperative targets greatly complicates testing procedures, since a given instrument may have enormous differences in performance, depending upon the surface under test. Similarly, different instruments may vary greatly in performance when measuring the same surface, depending upon on how the various instruments' technologies respond to that particular surface condition.

[viii] The iodine stabilized laser is one of the means to realize the meter from its definition.

To complicate matters further, even with a single imaging system and fixed targets, variation can still exist due to lighting differences. Some systems are affected by or rely on external lighting for illumination of the target and can yield differing measurement results based on the type of lighting (bottom lighting, ring lighting, etc.), the quality, position, and intensity of the light, and background contrast to the target. For such systems, this additional layer of complexity needs to be addressed in evaluating the measurement uncertainty.

Figure 3 shows the scanning results of two 25.4 mm (one inch) diameter spheres using a hand held scanning device. Although these spheres appear similar to the eye, and both are made of common manufacturing materials—one being nylon and the other polypropylene—the performance of the scanner in measuring their diameter and form (i.e. sphericity) varies dramatically. Complications such as material properties and angle of incidence of the measurement light imply that the measurement uncertainty of non-cooperative targets will be onerous to evaluate. Correspondingly it may be difficult to establish metrological traceability for a broad class of measurements without a case by case examination.

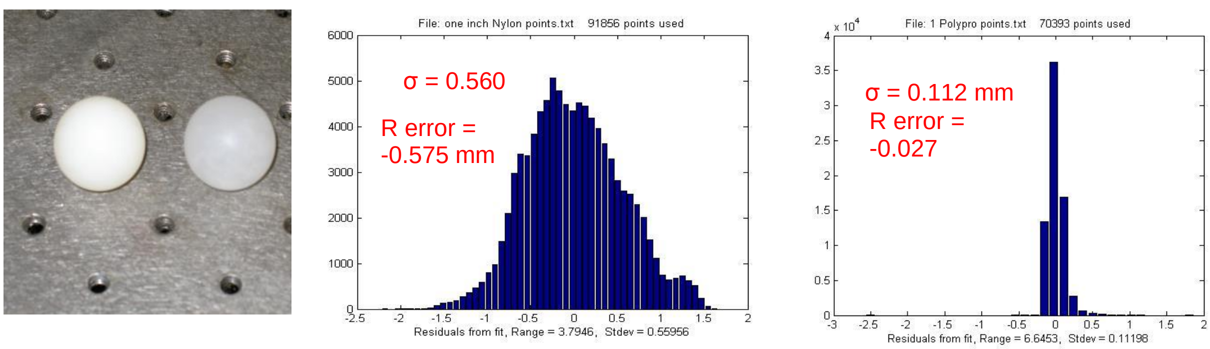

Figure 3: (left) photo of 25.4 mm nylon (L) and polypropylene (R) spheres; (middle) the fit residuals for the polypropylene sphere; (right) the fit residuals for the nylon sphere.

Figure 4 depicts a 1D test range where the measurand is the center-to-center distance between spheres. The 101.6 mm diameter spheres are made of titanium, selected because it provides a diffuse surface finish while maintaining good spherical geometry. (The form[ix] of each of the 101.6 mm spheres is typically a few micrometers; hence the center-to-center distance is a well defined measurand.) Figure 4 also shows the results of a recent 3D imaging instrument test on the 66 meter range by plotting the absolute value of the sphere center-to-center distance, assigning the nearest sphere to the instrument as the origin. The sphere center-to-center distance error shown is computed using both a least-squares fit where the radius is a fit parameter and using a constrained least-squares fit where the sphere radius is constrained to its calibrated value. The unconstrained fit, which would typically be the case in the workplace when measuring dimensionally unknown objects, shows significantly greater errors indicating that extracting geometrical parameters, e.g. size and location, will be a challenge for 3D imaging systems

[ix] The form error for a sphere is defined as the distance between two concentric spherical shells that just bound the surface of the sphere under consideration.

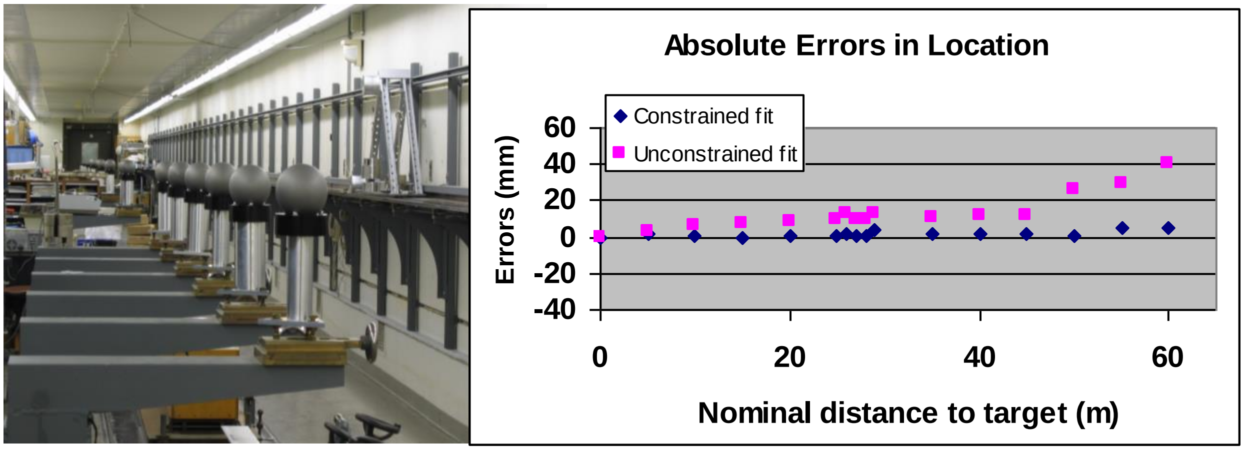

Figure 4: (left) A 1D test range spanning 66 meters using 101.6 mm diameter spheres as non-cooperative targets; (right) the absolute value of sphere center-to-center distance errors as a function of distance from the nearest sphere.

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