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Abstract: During the 1996 CMSC conference, undoubtedly one of the hottest topics was how to achieve traceability for the laser tracker. This paper reviews the concepts of traceability and measurement uncertainty from NIST's perspective, and explain how these topics relate to the effort of developing a standard for laser trackers. An update on this standardization effort, a preview of the Standard (including projected timetable), and what it means to users of this technology are discussed.

Key Words: coordinate metrology, laser tracker, measurement uncertainty, standardization, traceability

Introduction

At the Coordinate Measurement Systems Committee[1] (CMSC) 1996 annual conference, there was much discussion on the need for establishing traceability for the laser tracker. The importance of traceability stems from its use as a requirement of many purchasing contracts. Additionally, in order to maintain competitiveness in the emerging worldwide economy, many manufacturers and suppliers have begun implementing ISO 9000 quality systems and seeking ISO Guide 25 based measurement accreditation - both of which require traceability. This has led to a renewed and much intensified interest in the concept of traceability and the closely related concept of measurement uncertainty.

The laser tracker, for those that are unfamiliar, consists of a laser interferometer and two orthogonal rotary axes which steer the beam to automatically track a target (e.g., corner cube) in three dimensional space. The distance to the target, given by the laser interferometer, and the two angles from the rotary axes form a spherical coordinate system. Using this information, the coordinates of any point in the tracker's measurement volume can be determined in the tracker coordinate system. As with any three dimensional measuring instrument, these point coordinates can be used to construct the corresponding geometric element, e.g., planes, circles, spheres, etc.,

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[1] Committee of the American Society for Photogrammetry and Remote Sensing (ASPRS)

and to construct various relationships between the elements, e.g., distance between two circles, etc., For large scale measurements the laser tracker has several advantages over traditional linear axis coordinate measuring machines; namely, portability and a large measurement volume while maintaining sufficient accuracy. Because of these characteristics, the laser tracker has been gaining wide acceptance over the past few years in industries such as aerospace, automotive, and ship building.

Measurement Uncertainty

Although the idea of measurement uncertainty has been around for quite some time, the use of this concept was largely limited to the discussion of calibration results. Today, however, the proliferation of quality assurance and measurement services accreditation programs demands measurement uncertainty estimates at all levels of metrology. Measurement uncertainty is defined as the distribution of values, about the measured value, that could reasonably be expected to result for a particular quantity under measurement, see Figure 1. The de facto standard on the subject, *Guide to the Expression of Uncertainty in Measurement* (GUM) [1] and the NIST interpretation *NIST Technical Note 1297* [2], prescribe a method for developing an estimate of the measurement uncertainty. This method requires that all known sources of uncertainty be assigned a quantitative value (standard deviation) that represents its contribution to the measurement result. The uncertainty values may come from measurement data, expert knowledge, performance assessment standards, etc. These individual uncertainty components, known as standard uncertainties, are combined in a root-sum-of-squares (RSS) fashion and then adjusted for the applicable covariances to obtain the combined standard uncertainty. This result is then multiplied by a coverage factor to obtain the expanded uncertainty which represents the uncertainty interval (plus and minus unless otherwise specified) for the result of that measurement. The magnitude of the coverage factor indicates the level of confidence in the uncertainty interval analogous to the more familiar sigma limits, i.e., 1σ, 2σ, and 3σ. Therefore, assuming a Gaussian distribution, a coverage factor $k=1$ corresponds to a confidence level of approximately 68.3 %, $k=2$ a confidence level of approximately 95.5 %, $k=3$ a level of approximately 99.7 %, etc.

Strictly speaking, measurement uncertainty is only associated with the result of a measurement and is not a characteristic of an instrument or a measurement process. Therefore, we must be careful to distinguish between the contribution of an instrument to the uncertainty of a measurement and task specific measurement uncertainty. The latter is a much more comprehensive uncertainty estimate and should include all possible sources of uncertainty for the measurement. For example, with the laser tracker all of the error sources associated with the instrument itself, such as the geometry errors in the mechanical system, could be combined according to GUM methodologies to produce a point coordinate measurement uncertainty for the laser tracker. This would tell us how well the tracker could determine the location of any point within its measurement volume. However, this uncertainty estimate would not be very representative of the measurement uncertainty for the same tracker measuring the diameter and axis location of a large cylinder. In this case, the point coordinate uncertainty would be one of several components (not necessarily the dominant one) that would constitute the task specific measuring uncertainty. A complete task specific uncertainty statement would include additional uncertainty sources such as operator influence, part thermal expansion, sampling strategy, etc., and the coefficients describing the correlation among these sources. So we must be very specific in identifying under what conditions an uncertainty estimate applies and make sure that others who will make use of this estimate fully understand its limitations.

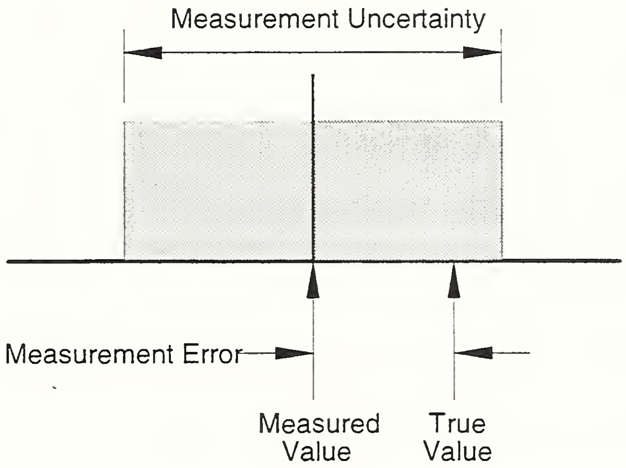

Figure 1. Difference between measurement uncertainty and measurement error (from [3])

Unfortunately, the laser tracker suffers the same difficulty as all three-dimensional coordinate measuring instruments when it comes to uncertainty estimation. The error mechanisms and the way these errors propagate through the measurement process are very complex and many times task specific. This makes the job of estimating uncertainty a very tough one. Currently there are only a few methods for achieving task specific measurement uncertainty estimation that are under review by the national and international metrology communities. These methods, in no particular order, are presented in table 1.

Table 1: Some recognized methods for establishing task specific uncertainty estimate for three dimensional coordinate measuring systems

Comparison Method	uses an independently calibrated master of same nominal size and shape to establish uncertainty of a specific measurement
Virtual Instrument	software simulation of feature measurements using an accepted model for error propagation.
Uncertainty Budgeting	all sources of uncertainty are assigned variances based on information from relevant sources and combined in a manner based on their influence on the measurement.

The most promising of these methods is the virtual instrument. Here, a valid error propagation model is developed for the instrument and combined with a model for all other non-instrument related error sources. These models are then used to simulate the measurement of a feature, many times while varying the relevant model parameters, to produce a distribution of possible results for that feature measurement. From this simulation process, an estimate of measurement uncertainty is obtained. As with the other methods, the complexity of the model and the integrity of the input parameters determines the applicability and accuracy of the uncertainty estimate. It is interesting to note that it is possible to either over estimate or under estimate the uncertainty given bad input data and/or an inadequate model.

Readers are cautioned not to confuse measurement uncertainty with measurement error, a term which is also used to describe the quality or expected quality of a particular measurement. As shown in Figure 1, measurement error is defined as the difference between the measured value and the true value. However, since the true value is by definition unknown, we use the "best estimate" of the true value which might be obtained from a number of independent measurements of that quantity or from a value agreed upon by convention. This is contrasted with measurement uncertainty which we previously stated is defined as the distribution of expected values about the measured value. The measurement uncertainty is, in effect, an estimate of all the possible measurement errors for the quantity being measured.

Traceability

The concept of traceability has historically been most closely associated with contractual agreements for the purchase of goods and services, especially those of the U.S. Department of Defense, and was primarily a means of facilitating commerce. There has really been neither a single accepted correct definition of the term nor a consensus of what is required to demonstrate traceability. What traceability means and how it is enforced was left to the discretion of the organization that was mandating traceability. In most cases, all that was required was the ability to show a relationship between a given measurement and the basic unit of length through a calibration "paper trail" [4-6]. This established that everyone was using the same unit of length without, however, making an assessment on the accuracy of the transfer(s). To further add to the confusion, the organization mostly closely associated with traceability in the United States, NIST, has little to do with the definition or administration of the concept. In fact the NIST calibration user's guide states [7]:

> NIST does not define nor enforce traceability except in its National Voluntary Laboratory Accreditation Program (NVLAP). Moreover, NIST is not legally required to comply with traceability requirements of other federal agencies; nor do we determine what must be done to comply with another party's contract or regulation calling for such traceability. However, NIST can and does provide technical advice on how to make measurements consistent with national standards.

The primary role of NIST with respect to traceability is as the keeper and disseminator of the SI base units (and some derived units) for the U.S., hence the term "traceable to NIST".

Recently, a more rigorous interpretation of the concept of traceability has been gaining wide acceptance. The *International Vocabulary of Basic and General Terms in Metrology* [8] defines traceability as:

> Property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

Using this definition, measurement uncertainty is now a necessary component for establishing traceability. Besides being able to show an unbroken link to the unit of length, the measurement uncertainty associated with each transfer must be documented as well.

As with measurement uncertainty, we must be careful to state exactly for which measurement(s) traceability has been established. In the case of the laser tracker, it is possible to individually calibrate the laser interferometer, establishing conformance to the SI basic unit of length at a given level of uncertainty. Similarly, the rotary axis angular encoders can be calibrated, using an artifact and/or closure techniques, and assigned an uncertainty. (The traceability of the encoder ultimately derives from the fact that there are 2π radians in a circle.) At this point, the interferometer and each rotary encoder would be independently traceable by the above definition. However, this is not sufficient to constitute traceability of the laser tracker itself since the uncertainty statement would be incomplete. As in the previous discussion on measurement uncertainty, we would have failed to consider the complex interrelationship between these subsystems as well as other sources of uncertainty. What is ultimately needed is the ability to generate task specific measurement uncertainty, i.e., individual part features, to insure traceability for the measurement at hand. So the focus must be to strive for traceability of measurements made with the laser tracker rather than traceability of the tracker itself.

The Road to Laser Tracker Traceability

Given NIST's mission and policies on traceability and measurement uncertainty, it was decided that the best way for NIST to contribute would be to initiate and support a standards working group whose focus would be measurement uncertainty estimation as a means for establishing traceability for laser trackers. This working group operates under the auspices of the American Society of Mechanical Engineers (ASME) and carries the designation B89.4.19 - Optical Coordinate Measuring Machines. This is an all voluntary group, open to knowledgeable and interested parties, with the requirement of striking a balance among user, manufacturer and academic participants. Currently the working group meets one full day, three times a year (at various locations around the U.S.), to review progress and to plan the next phase of development.

The final output of this group will be submitted to American National Standards Institute (ANSI) for consideration as an American National Standard. This, as are all ANSI standards, will be a non-compulsory standard which only achieves status through industry acceptance. Additionally, there is an opportunity to submit this working group's output as a starting point for an ISO standard. There are currently no known efforts to standardize the performance evaluation and measurement uncertainty estimation of the laser tracker outside the U.S., presumably because the U.S. is currently the principal market. However, it is not expected that this will last for long so there is an added incentive for success, to have the U.S. position on this technology effectively represented.

Schedule/Progress

The first step in the standardization process was to hold a focus group meeting at NIST in August of 1996. We invited the two principal commercial manufacturers of laser trackers along with some users who had previously expressed an interest in developing uncertainty statements for this type of instrument. The two days of meetings were used to assess the current state-of-knowledge in this area and to review the related concepts in order to form a solid and common foundation for any subsequent efforts to proceed. This pre-meeting was deemed a necessary prelude to the standard meeting in order to facilitate a "fast tracking" for this proposed standard. A typical standard development cycle is 3 to 5 years with an additional year required for public comment and publishing. It was the opinion of the those present at the NIST focus group meeting, and that of U.S. industry as evidenced by the CMSC conference discussions, that this time frame needed to be severely compressed.

Since the NIST focus group meeting, there have been three meetings of the standards working group. Working both during and in-between these meetings there has been significant progress made toward a draft standard. Several tests have been proposed and carried out by multiple individuals in order to evaluate the validity and practicality of these tests. It is anticipated that a final draft version of the standard will be ready to present to the full B89 committee on dimensional metrology at its January 1998 meeting. At that point it will undergo extensive review by the committee prior to presentation for a public review and comment period. If everything goes as planned, the Standard could be ready for publication as early as mid-1999.

Along with the ultimate goal of developing a methodology that will allow users to estimate the uncertainty of measurements made with the laser tracker, the focus group meeting identified several related areas where a standard could benefit this technology. The first is the recommendation of a series of tests that can be used to calibrate the tracker. This calibration procedure will be much like procedures performed by cal/cert labs, at major organizations, for many other metrology instruments. The calibration process should be distinguished from the set of procedures initially used by the manufacturer to "align" the laser tracker - that is determine and compensate for the known systematic errors of the instrument. Calibration involves the thorough testing of the tracker performance, but because of different tracker designs, may not yield quantitative results necessary for tracker alignment. It is expected that the results of the calibration procedure(s) will yield point coordinate uncertainty estimates for the tracker. Additionally, this procedure could be used for acceptance testing during a laser tracker purchase and will, therefore, contain some elements necessary to facilitate this "buy-off".

There was also strong support, amongst the focus group, for the development of some sort of an interim test. The purpose of an interim test is to provide the operator with assurance that the instrument is still performing at or near the same level as when it was last calibrated. As it is the intent that this test be performed often, e.g., when the tracker is relocated, a major concern will be the time required to conduct the test. Therefore, the test(s) will be designed to provide the minimum information necessary to establish confidence in the tracker's performance in the least amount of time possible. The major sections that are expected to comprise the proposed standard are shown in table 2 below.

Table 2: Proposed sections of the laser tracker Standard along with a brief description

Section Title	Brief Description of Contents
Scope	
Definitions	includes a glossary of relevant terms and a section on laser tracker classification
Environmental	specification of measurement environment and tests that assess environmental influence on tracker performance
Performance Tests	
Interim tests	rapid in-the-field assessment to establish that performance has not changed since last calibration
Calibration tests	tests of instrument and subsystems with the intent of establishing point coordinate GUM type uncertainty
Artifact and Test Equipment Specifications	describes the requirements for artifact and test equipment that are used in the execution of the standard.
Related Appendices	these are designed to facilitate use of the standard and provide guidance on good metrology practices

This is a typical format for the B89 committee's standards on dimensional metrology. It differs somewhat in philosophy from other B89 standards since it has as a primary goal the estimation of the instrument contribution to the measurement uncertainty.

So what does this mean for the average user? While we have not yet solved the more complex problem of estimating task specific measurement uncertainty, the proposed standard should succeed in unifying tracker specification, and in facilitating buy-off and measurement assurance programs. It attempts to standardize areas of the laser tracker performance where previous tests were weak or nonexistent. In the meantime, work is continuing on the development of the virtual laser tracker. Significant progress has already been made with this method in the CMM community and it is foreseeable that it could easily be transferred to the laser tracker. Once a valid instrument error propagation model is developed and integrated with the appropriate portions of the CMM virtual instrument, task specific measurement uncertainty for the laser tracker will be achieved.

Summary

We have reviewed the question raised at the 1996 CMSC annual conference concerning the establishment of traceability for the laser tracker. Additionally, the concepts of traceability and measurement uncertainty were briefly explored along with the relationship between these two concepts and how they relate to the laser trackers. A potential solution to the posed question, within the constructs of NIST mission and policies, was presented which involved the initiation of an ASME working group to address the performance evaluation and measurement uncertainty of laser trackers. The steps taken to form the working group, proposed schedule, and the progress of the group to date were explained along with an outline of the proposed standard. Finally, a brief discussion of the anticipated benefits was presented.

References

[1] International Organization for Standardization (ISO), Technical Advisory Group 4 (TAG 4), Guide to the Expression of Uncertainty in Measurement, ISO, Geneva, Switzerland, 1993.

[2] B.N. Taylor and C.E. Kuyatt, Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, NIST Technical Note 1297, National Institute of Standards and Technology, 1994.

[3] S.D. Phillips, Performance Evaluation (Chapter 7), in John A. Bosch (ed.) Coordinate Measuring Machines and Systems, Marcel Dekker, Inc., New York, p 138, 1995.

[4] B.C. Belanger, Traceability: An Evolving Concept, Standardization News, Vol. 8, No. 1, American Society for Testing and Materials, pp. 22-28, 1993.

[5] E.L. Garner, S.D. Rasberry, What's New in Traceability, Journal of Testing and Evaluation, Vol. 21 Num. 6, pp. 505-509, 1993.

[6] D.A. Swyt, The International Standard of Length (Chapter 7), in John A. Bosch (ed.) Coordinate Measuring Machines and Systems, Marcel Dekker, Inc., New York, p 123, 1995.

[7] NIST Calibration Services Users Guide, NIST Special Publication 250, Calibration Program, National Institute of Standards and Technology, World Wide Web Edition, Chapter 1, 1997.

[8] International Organization for Standardization (ISO), Technical Advisory Group 4 (TAG 4), International Vocabulary of Basic and General Terms in Metrology, ISO, Geneva, Switzerland, 1993.