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Proposed procedure for a distance protocol in support of ASTM-E57 standards activities on 3D imaging

J.-A. Beraldin^{*}, L. Cournoyer, M. Picard and F. Blais
Institute for Information Technology,
National Research Council Canada, Ottawa, ON, K1A 0R6, Canada

ABSTRACT

The performance of 3D Imaging Systems needs to be evaluated using a common terminology and test procedures. This evaluation is necessary because three-dimensional imaging systems are measuring instruments and the spatial coordinates they provide are only estimates of the 3D surfaces being sampled. These coordinates need to be completed by a quantitative statement about their uncertainty to be meaningful. The statement of uncertainty is based on comparisons with standards traceable to the national units of length (SI units). We describe and present experimental results of a procedure to evaluate distance measurement uncertainty of medium range laser scanners (range between 2-100m). The procedure is based on the evaluation of Point-to-Point distance errors using custom made Reference Test Object (RTO) and a certified 3D laser tracker as a reference. This work is proposed as a possible protocol to the American Society for Testing and Materials (ASTM)-E57.02 3D Imaging Systems standards committee on test methods.

Keywords: 3D imaging, range cameras, accuracy, measurement uncertainty, calibration, metrology laboratory, systematic errors, standards, E57

1. INTRODUCTION

The American Society for Testing and Materials (ASTM) Committee E57 on Three-dimensional (3D) Imaging Systems¹⁻² was formed in 2006. This committee addresses issues related to 3D imaging systems, which include, but are not limited to systems based on time-of-flight technology and optical triangulation. The need for standards is mainly driven among other things by users and product developers who are concerned with 1) the applicability of a given system to the task at hand (fit-for-purpose), 2) the ability to fairly compare across instruments, 3) instrument warranty issues, 4) costs savings through 3D imaging. The evaluation and characterization of 3D imaging system require the definition of metric performance. The performance of a system is usually evaluated using quality parameters such as spatial resolution/uncertainty/accuracy and complexity. These are quality parameters that most people in the field can agree upon. The difficulty arises from defining a common terminology¹ and procedures to quantitatively evaluate them through metrology and standards definitions. We describe and present experimental results for a procedure to evaluate distance measurement uncertainty (*distance protocol*) using medium range laser scanners (range between 2-100 m). The procedure is based on the evaluation of Point-to-Point distance errors using custom made reference test objects based on flat plates (see Figure 1) and comparison to measurements obtained from a certified 3D laser tracker. The accuracy specification of the laser tracker was provided by the manufacturer using the procedure reported in the ASME B89.4.19 standard³ using the maximum permissible error (MPE). The tests were conducted for distances between 4 and 23 m.

Figure 1. Laboratory set-up and Reference Test Object (RTO) for the proposed distance protocol.

^{*} angelo.beraldin@nrc-cnrc.gc.ca

2. REVIEW OF LITERATURE ON THE TOPIC

Three-dimensional imaging systems produce a 3D digital representation (e.g., point clouds, 3D images or range maps) of a surface: at a given standoff distance, within a finite volume of interest, with a certain measurement uncertainty, and, with a known spatial resolution⁴⁻⁵. During the last 16 years or so, many publications have described different approaches to assess the performance of the data acquired by a 3D imaging system in the absence of an international standard. In most publications, the authors strived to attach to the measured coordinates produced by the 3D imaging system they tested a quantitative statement about their uncertainty. Unfortunately, comparisons with standards traceable to the national units of length (SI units) were not always clear. An uncertainty statement is required in order to decide the fitness for purpose of a measurement for a given 3D imaging system. In the field of metrology, mathematical tools, terminology (ISO VIM)⁶ and methodologies exist to estimate and report uncertainty, e.g. ISO Guide to the Expression of Uncertainty in Measurement (GUM)⁷. The notion of accuracy is considered a qualitative concept and uncertainty is the quantitative statement of accuracy. At the moment, many manufacturers compare their 3D imaging systems to instruments for which standards do exist, e.g. Coordinate Measuring Machines (ISO 10360-2, VDI/VDE 2617 and ASME B89.4.10360.2), laser trackers (ASME B89.4.19), etc. This can be useful in some applications but not for all. Specific characteristics of optical 3D imaging systems require unambiguous standards aimed at them exclusively. More experiments need to be done in the context of metrology. Standards committee work will be crucial in order to lay down a clear standard for 3D imaging systems.

2.1. Short range (distance < 2 m)

Before 1999, only a limited number of publications described short-range 3D imaging system performance evaluation. These 3D imaging devices are mainly composed of laser and pattern projection triangulation-based systems. In many cases, these publications presented results for the evaluation of custom built 3D imaging systems or systems that are no longer available. Buzinski et. al. (1992) characterized the performance of triangulation-based probes for CMM applications⁸. The authors looked at the mechanisms that generate systematic depth errors on sharp edges and reflectance changes. El-Hakim et. al. (1995) evaluated a number of custom built laser scanners using prismatic artifacts⁹. Beraldin et. al. (1999) evaluated a prototype laser scanner mounted on a rotation stage¹⁰. They evaluate measurement uncertainty as a function of distance and surface reflectivity. With an increased availability of commercial 3D imaging systems and a recent need to evaluate them for critical projects, the body of work has augmented considerably in recent years. To name a few, Xi et. al. (2001) proposed a method to improve the accuracy of a line scanning system mounted on a CMM¹¹ and Beraldin & Gaiani (2005) evaluated the performance of four close range 3D vision systems for industrial design applications¹². Van Gestel et. al. (2008) propose a test method for line scanners on CMMs that uses a planar test artifact¹³. For the authors, the standard deviation of the scanned reference plate is an indication of the random error (measurement noise) of the scanner. The distance between plates, scanned in different scanner probe positions, is an indication of the systematic error. Without 3D imaging systems standards and considering the wide use of 3D imaging systems in the manufacturing industry (SME 2008)¹⁴, the quantitative evaluation of uncertainty of 3D imaging systems remains the responsibility of the user.

2.2. Mid-range to long range

For mid-range (2 m < range < 100 m) and long-range (range >100 m) 3D imaging systems, accuracy evaluation of laser scanners was undertaken on some custom built and many commercial scanners. Comparison of a custom built 3D laser scanners and a total-station was studied by Beraldin et. al. (1997) for the inspection of a module of the international space station¹⁵. Johansson (2002) compares distances between targets obtained with a survey and three commercial time-of-flight laser scanners¹⁶. Pflipsen (2006) looks at volume estimation for a commercial time-of-flight system and a total station¹⁷. Hebert and Krotkov (1992) analyze a class of 3D imaging system based on time-of-flight phase measurement principle in the context of computer vision and robotics¹⁸. They identified the nature and cause of key problems that plague measurements from this class of devices. They classify problems related to the signal-to-noise ratio, artifacts caused by insufficient temperature compensation and surface topology. Paakkari and Moring (1993) describe a test method developed for internal use¹⁹. It estimates performance factors such as resolution, repeatability and accuracy. Boehler et. al. (2003) present a large body of tests and compile results tables for five quality parameters, i.e. angular accuracy, range accuracy, resolution, effects of edges, effect of surface reflectivity²⁰. The tests were performed on ten commercial laser scanners. Clark and Robson (2004) investigate the performance of a commercial time-of-flight laser scanner in making measurements to a variety of surfaces of specified color characteristics under laboratory conditions²¹. They observed a significant systematic range discrepancies which they correlated to the color of each surface with

respect to the wavelength of the laser used. A correction was demonstrated to be applicable to diffusely reflecting surfaces. Mechelke et. al. (2007) perform a series of tests aimed at estimating derived distances from point clouds of a 3D test field for accuracy test of distance measurements in comparison to a reference, accuracy tests of inclination compensation, influence of laser beams angle of incidence on 3D accuracy, investigations into the scanning noise and the influence of object color on distance measurements²². Salo et. al. (2008) deal with component calibration of a time-of-flight phase measurement laser scanner²³. For a range of 1 to 30 m, the observations were compared to the results obtained with a robot tacheometer. The results indicated that the relative distance measurements were biased by both constant and periodic non-linear error. They also observed that the wavelengths of detected periodic errors are correlated with the wavelengths of the modulation frequencies of the instrument, or their harmonics. Periodic errors found were corrected with the error function calculated by Fourier analysis. The problem with commercial systems stems from the fact that access to the electronic circuits for phase measurement and for control is not allowed by manufacturers. Other authors like Lichti et. al. rely on a self-calibration on top of the manufacturer supplied calibration²⁴⁻²⁵. A draft protocol to evaluate the range error (*ranging protocol*) in 3D imaging systems is proposed by Cheok et. al. (2007)²⁶. Two rounds of tests were conducted in 2007 to evaluate range error based on this proposed ranging protocol. The authors found that sixteen combinations using planar targets could be completed in one day. Measuring the "true" distance from the 3D imaging system to the targets was performed using a laser tracker during the first round of tests and a total station during the second round.

2.3. Comments on the need for a standard(s)

In all such evaluations and comparisons, each work used different approaches, terminology, types of data sets, and commercial scanners at the time of the tests. Though, all of this work was probably very useful to the authors and possibly many expert users, it is not easy for someone that is not an expert to enter the field of 3D and to select an imaging system for a given task at hand (fit-for-purpose), or to allow for a fair comparison across instruments. For manufacturers, because of the variability of these tests, warranty issues may become problematic in the future. Unless, standards committees organize the information present in all those very helpful tests into a consistent standard that will satisfy the community of manufacturers and general users, confusion will persist.

2.4. Standards being developed

For a 3D imaging system standard to become useful, the terminology must be clear and universal. The standards should cover the required acceptance and reverification tests for geometric quality parameters and they should dictate the procedure to follow. Without standards, different projects may not achieve the expected quality. In Germany, VDI-The Association of German Engineers published a guideline called VDI/VDE 2634²⁷. It has been prepared for short-range optical 3D vision systems. It contains acceptance testing and monitoring procedures for evaluating the accuracy of systems based on area scanning (e.g. triangulation-based pattern projection systems). A standards committee known as E57 has been formed by the American Society for Testing and Materials (ASTM)¹⁻². It has the mandate to work on the development of standards for 3D imaging systems. Their initial focus will be on standards for 3D imaging systems specification and performance evaluation for applications like construction, surveying, manufacturing, historic preservation, forensics to name a few. E57 has four technical subcommittees that maintain jurisdiction over these standards. They are E57.01 on terminology, E57.02 on test methods, E57.03 on best practices and E57.04 on data interoperability. Cheok et. al. (2008) present an update of the activities of this ASTM committee. The subcommittee E57.01 developed a terminology standard, ASTM E 2544-08b¹, in 2008. This standard contains terms that are specific to 3D imaging systems (*to name a few*: 3D imaging system, angular increment, beam diameter, instrument origin, point cloud, range). Additionally, this standard contains other metrology terms that are defined in other standards relevant to the 3D imaging community. The scope of subcommittee E57.02 is "To develop a standardized set of data collection procedures, data analysis and reporting methods for characterizing the measurement performance of 3-D imaging systems." The subcommittee has been working on a draft protocol to evaluate the *ranging performance* of a 3D imaging system²⁶. This subcommittee faces several issues. A fundamental issue is the purpose of the test either to allow for comparison of instruments using standard targets or to evaluate instruments using real world materials. The decision at the January 2008 ATSM Committee Week meeting was to use a standard target (i.e., similar optical properties for the wavelengths of interest), develop test procedures and evaluate these procedures²⁸. More information about the other two committees appears in the paper by Cheok et. al. (2008). Other committees may get involve in the future on standards definitions for 3D imaging systems associated to their target market, e.g. ISO/TC172 SC6: Optics and optical instruments/ Geodetic and surveying instruments, ASME B89.4: Coordinate measuring technology and ISO/TC 213/WG 10: Coordinate measuring machines.

3. INSTRUMENTS & SOFTWARE FOR THE PROPOSED PROTOCOL

3.1. Reference instrument: laser tracker

The Faro® Laser Tracker Model X from FARO Technologies Inc., was used as reference in the proposed distance protocol. It acquires absolute distance and two direction angles using a spherically mounted retro-reflector (SMR) that must touch the surface or feature of interest. The SMR consists of a corner cube retro-reflector mounted inside a stainless steel sphere with certified dimensions that returns the laser back to the laser tracker. The current system uses a distance measurement device known as Absolute Distance Measurement (ADM) that is based on proprietary time-of-flight technology. The result is 3D coordinate measurement system that measures up to 35 m (diameter 70 m) with horizontal and vertical envelopes of $\pm 270^\circ$ and $+75^\circ$ to -50° respectively. The tracker comes with performance specifications and test results according to ASME B89.4.19 (2006). This new standard for laser tracker performance evaluation is the only accepted procedure for testing laser tracker accuracy. The manufacturer conforms also to ISO-17025 accreditation based on this procedure. According to the FARO® documentation, the maximum permissible error (MPE) is $20 \mu\text{m} + 0.8 \times L$ $\mu\text{m}/\text{m}$ in ADM mode and $36 \mu\text{m} + 6 \times L$ $\mu\text{m}/\text{m}$ in the transverse mode.

3.2. 3D Imaging System Under Test (SUT): time-of-flight laser scanner

The Surphaser® Model HS25X (MR Configuration) from Basis Software, used as the SUT, is described as a hemispherical time-of-flight phase shift laser scanner. It has a field of view of $360^\circ \times 270^\circ$ (horizontal $\times$ vertical or azimuth $\times$ elevation). Figure 2 shows the metrology laboratory as acquired by the hemispherical 3D laser scanner. One may note the distorted straight lines. This is due to the 2D representation of a 3D image used in the figure.

Figure 2. Example of a mid-range laser scanner based on time-of-flight principles (Surphaser Model HS25X) that captures 3D coordinates using a spherical laser scanning mechanism: a) laser intensity image generated by the laser scanner where the vertical axis depends on the rotating scanning mirror angle and the horizontal axis, on the rotation motor angle, b) same parameterization as in (a) but the distance information is encoded in grey levels.

For this test protocol, the scanner was programmed to scan a limited angle in the horizontal direction. The vertical angle could not be modified because the rotating mirror operates only in continuous mode. Table 1 lists the main performance parameters extracted from the manufacturer's specifications sheets. These were used to guide the design of the Reference Test Objects (RTO) and calculate the expected uncertainty for the parameters obtained from geometrical fitting.

Table 1. Performance parameters of the Surphaser® 25HSX-MR hemispherical laser scanner taken for specification sheet.

Performance parameter	Value
Maximum horizontal field of view	360°
Maximum vertical field of view	270°
Horizontal-Vertical angular resolution/uncertainty	39 μrad /145 μrad
Maximum horizontal-vertical point spacing	120 points/degree (145 μrad /point)
Ambiguity range	27 m
Range noise at 5m; 90% Lambertian surface; 2-pass	0.1 mm
Laser spot size at 5 m	2.3 mm
Laser spot size at 27 m	6.2 mm
Total target position uncertainty	<1 mm @ 15 m

3.3. Reference Test Object (RTO)

From the system's performance parameters and measurement principle, it is critical that a 3D RTO be selected with a known surface reflectivity, form factor and finish. Location and orientation will also affect performance. As a rule of thumb, an object should have a form error (e.g. flatness) 4-5 times smaller than that of the System Under Test (SUT) can measure during its evaluation. For instance, a scale bar made of a stable material with low thermal coefficient of expansion (TCE), e.g., SuperInvar, Invar (TCE~2 ppm/°C) or some composite materials, can be used as an RTO. Other RTOs with known features and surfaces can be manufactured from stable materials and measured with instruments that have adequate accuracy compared to the SUT. The test surfaces (plates) on the selected RTOs are made of aluminum which has been treated using a special vapor blasting process and the plates are measured for form (flatness, angles), reflectance factor using the Diffuse:Normal (*de*:8) standard method conditions (as described in ASTM 1164-02 document³⁶), and roughness using Ra parameter. The location of plates holder is measured with four SMRs. The location of the three spheres is measured with the laser tracker using one SMR touching the sphere surface at twelve locations. These SMRs are made of 440C Stainless Steel and the ball sphericity is better than 1.27 μm (0.00005"). The Retroreflector Apex position is known to within 2.54 μm (0.0001") of the center of the ball.

3.4. Software (SW) means: Analytical tools for geometric fitting

Geometrical RTO like flat planes, spheres, cylinders, and cubes offer us a common way to compare 3D imaging systems. They can be purchased at a reasonable cost and they can be accompanied by a certificate. For instance, the estimation of a surface requires an excellent knowledge of parameter estimation of geometric models from noisy data³⁰. Caution should be exercised because the noise along the (x, y, z) axes is correlated, anisotropic and inhomogeneous^{29,31}. In some cases, surfaces may be translucent. These surfaces will have a detrimental effect on both triangulation and time-of-flight 3D imaging systems³²⁻³⁴. As noted by Kanatani³⁰, in some situations "*the removal of systematic errors and outlying data is more important than optimal estimation on the Gaussian noise assumption*". We used flat plates with a surface having a high enough reflectance to maximize signal-to-noise ratios. Spheres are used to create a virtual line that was used to intersect the plates (see next section for details). Unfortunately, if one uses a commercial analysis package, it is not clear what the underlying algorithms for fitting are. We use standard best-fit algorithm that performs a pure least-squares approach with outliers rejection in the IMInspect® interface from InnovMetric® Software Inc. Spheres are fitting to the measured data using the same software. The fitting of spheres from noisy 3D data was studied by Witzgall et. al. for the case of orthogonal fitting and fitting in the scan direction³⁵.

4. PROPOSED PROCEDURE & EXPERIMENTAL RESULTS

In the ASTM E57.02 sub-committee on Test Methods under new practice WK12373^a, scope 1.1 states the following "*This practice covers evaluating the performance of three-dimensional (3D) imaging systems based on many different criteria. One such criterion is the range error of the system for which a protocol is proposed in this practice*". This suggests a protocol based on the measurements along the range direction only. This can also be interpreted as implicitly meaning that a change in scanning angle is not supposed to occur. In other words, the laser beam emitted by the 3D imaging system points in one direction only. On the official terminology document E-2544-08b¹ Standard Terminology for three-Dimensional (3D) Imaging Systems, the term *range* is defined as "*the distance, in units of length, between a point in space and an origin fixed to the 3D imaging system that is measuring that point*".

We are of the view that a protocol based on range measurements *only* would be specific to the types of system that are characterized by collinear projection and collection of laser light. Most time-of-flight systems have that property. They are also known as monostatic. Only a handful of time-of-flight systems are non-monostatic. Therefore, the protocol would exclude the types of systems that have a projection and a collection path that are distinct, i.e. with a baseline. This class of systems account for all triangulation-based systems like those that use dense stereo, laser scanners and white-light pattern projection. Furthermore, it is important to use a system in the same manner as it would be in a real situation. For instance, if a system needs to scan an object to generate 3D images then, it must scan in a similar fashion when one tries to evaluate it with a given protocol. Besides, if a system needs to stop scanning and the laser kept on, it must still stay eye-safe in order to fulfill safety regulations. We propose a method that is *not* strictly based on *range* measurement, but that measures known RTOs like flat plates distributed along a line of sight that starts from the SUT and that uses

^a New Practice for Evaluating the Range Performance of Three-Dimensional (3D) Imaging Systems
<http://www.astm.org/DATABASE.CART/WORKITEMS/WK12373.htm> (last accessed 23 Oct. 2008)

normal modes of operation of that SUT. The proposed method does not require a perfect alignment of those plates with respect to each others and with the SUT center line or origin. We evaluate *measurement errors on distances* between plates in relation with the distances from the SUT and the angle of incidence of the surface of the plates at five different angles: 0° , $\pm 40^\circ$ and $\pm 60^\circ$. This last characteristic is the same as proposed in the E57 test Methods. Those five angles were selected in order to evaluate the impact of surface angle on distance measurement errors (random and systematic).

Before we start describing the details of the method, it is important to define the measurand as per ISO VIM⁶ (“Quantity intended to be measured”). In the present distance protocol, the two measurands are E_m and STD_m . The former refers to the measurement error between the distance of two points on the imaged (in 3D) flat plates and the latter, the standard deviation of the errors resulting from a best-fit plane equation through the data set acquired on the plate as a function of distance. These will be evaluated under the following set conditions: the number of points collected per unit area ($N/Area$), time elapsed for data collection (S_e), ambient temperature (T_a), ambient pressure (P_a) and ambient (RH_a). It is within the working group of subcommittee E57.02 on a proposed *ranging protocol* that we present this *distance protocol*.

Figure 3. Schematic diagram of the set-up showing the tripod fixed locations. A plate holds three spheres that is positioned at two locations, one at the closest location (left) to the 3D imaging system and the other at the farthest (right). The plate is physically moved to the farthest position. It rests on kinematic mounts. This top view shows only one sphere.

As per WK12373 committee work documentation (not available for distribution yet)^{26,28}, these two measurands have to be reported in relation to the following variables:

- 1) Four distances between four measured plates and a reference plate (see Figure 3). The four measured plates should be located anywhere between 0 and 25%, 25 and 50%, 50 and 75%, and, 75 and 100% of maximum range capability of the system under test (SUT). The reference plate should be located anywhere between the SUT and the first measured plate. It is not possible to locate the same points on the plate surface and therefore, a set of spheres mounted (see Figure 5) in a similar way as the flat plates are used to create virtual vectors that connect the spheres center at the first plate location to those at the last location. These virtual vectors (lines) intersect those flat plates in a systematic way (Figure 4) creating virtual 3D points (coordinates) used for comparison.
- 2) The angle of the plates are 0° (see Figure 6a), $\pm 40^\circ$ (see Figure 6b), $\pm 60^\circ$ (see Figure 6c).

Figure 4. Schematic diagram of a side view of the set-up used to evaluate the three vectors passing through three spheres at two locations, i.e. at the closest location (left) to the 3D imaging system and at the farthest (right).

For the first measurand E_m , the distance should be compared with a true value, i.e., one with an uncertainty that is much smaller than what the SUT would be capable of accomplishing. The method compares the distance taken between the same virtual 3D points measured with the SUT and a reference instrument producing what is considered true values. In the present protocol, a laser tracker manufactured by Faro (Faro Laser Tracker Model X) was used as reference (see section 3.1) and a Surphaser Hemispherical Laser Scanner Model HS25X from Basis Software as SUT (see section 3.2).

Figure 5. Elements used for the *distance protocol* in the NRC-IIT metrology laboratory: a) the five tripods at the positions needed for the protocol, b) the four SMRs and the spheres plate, c) laser scanner with the first position of the spheres plate.

The experimental work on this proposed distance protocol was conducted within stable environmental conditions found in NRC-IIT's 3D Imaging Metrology²⁹. During the two-day experiment, the average temperature was 20.00°C with a standard deviation of 0.02°C. The average relative humidity was RH=49.0% with a standard deviation of 2.5%. The second experiment was conducted in a hallway next to the laboratory. The temperature and humidity were not controlled.

Figure 6. Reference plates: a) the four SMRs and the plate at 0° mounted on a back plate, b) the two angle plates at +40° and -40° from the 0° plate, c) the two angle plates at +60° and -60° from the 0° plate mounted on the same back plate holding the four SMRs (not all visible).

Let us look at the error caused by a slight misalignment when a reference plate is moved from one tripod to the next. As discussed, the tripods are aligned using a simple procedure that involves a bubble level and a visual inspection. This does not guaranty a perfect alignment put in any case it is neither required nor necessary. The repositioning of the structure supporting the reference plates is repeatable. The plates are mounted on the supports and the tolerance is given by the machining of the components and the assembly. The difference between the measured position of the plate and its expected position is given by the quantity d_e : in position 1 (see Figure 7):

$$d_e = t_s \tan(\alpha) \quad (1)$$

where d_e is the longitudinal shift in distance caused by a misalignment between plates, t_s the transversal shift due to an error in plate location, α is the angular difference between expected and real angles of the flat plates. Typical values of t_s are ± 2 mm and α , $\pm 2^\circ$. For the 0° plate, this yields an error of ± 70 μ m which is smaller than the expected uncertainty of the laser scanner. For the other two plates ($\pm 45^\circ$, $\pm 60^\circ$), we need to correct for the longitudinal shift t_s . In an ideal

situation, the plates would be perfectly parallel and centered on a common axis. The expected positions are the distance between plate's centers. In reality, misalignment needs to be compensated for, therefore the use of virtual reference lines from spheres (see Figure 7).

Figure 7. Diagram showing the effect of positioning error of the reference plate from one tripod to the next (not to scale).

The difference between measured distances and true distances are calculated along virtual reference lines (vectors). The method uses one sphere center located at the reference position 0 and a second sphere center at the farthest position (see Figure 8a). The intersection between a plate (after a plane equation has been fitted through the data) and this reference line define a 3D point. This is the base of comparison for the distances between the positions that correspond to E_m . The spheres and the plates are measured by both the reference instrument (i.e. laser tracker) and by the SUT. The distances obtained as a result of this process can be compared and the difference is reported as the measurement error in distance E_m . We put three spheres per plate and hence three reference lines per tripod positions. These spheres are moved with the mobile mechanical setup at the two positions (position numbers 0 and 4) required to define the reference lines.

Figure 8. Screen snapshots taken from: a) Cam2® MeasureX® interface from FARO Technologies Inc. showing the reference lines, the spheres and the planes representing the four SMRs at the five locations of tripods b) IMInspect® interface from InnovMetric® Software showing the measured planes from the Surphaser® Laser Scanner data.

The plate at 0° is mounted on a mobile mechanical setup along with four Spherical Mounted Retro-reflector (SMR) that are measured with the Laser tracker. The distances between the plate and the SMR positions are measured only once with the tracker. For each distance to be measured, the mechanical setup holding the plate is moved onto a rigid tripod which contains three semi-kinematic mounts interface that provide sufficient reliability for repositioning and an excellent stability. This is verified on a separate procedure prior to the execution of this protocol. Every time a plate is measured with the SUT, the locations of the four SMR are measured with the tracker. A complete model of the measured plate positions is built using the tracker data at the same time it is scanned with the SUT (Figure 8a).

Figure 9. Block diagram summarizing the processing of the data for the laser tracker.

After the five positions have been scanned using the 0° plate, the target is changed for the angle plates at $\pm 40^\circ$ and the sequence is repeated for the five positions. The distances of the four SMRs relative to the plates are measured only once, because it does not change when the mechanical setup is moved to another tripod. The same procedure is repeated for the plates at $\pm 60^\circ$. One of the lines of reference is used to determine the comparison points. In the case of the plates at the two angles other than 0° , only one line is used for each angled surface. For example, for the plate located at the top of the setup, the reference line is the one created using the sphere located at the top of the mounting plate. The same reference line is defined using the data taken with the tracker on the spheres and the virtual points have been created. A set of five coordinates points are obtained. The distances are computed between the intersection points from the tracker data. Figure 9 summarizes the processing steps for the laser tracker and Figure 10 for the SUT. Those distances are then compared with the distances measured from the SUT scanned data. Table 2 shows the differences E_m . The experiment was conducted in an environmentally controlled laboratory at NRC-IIT ($20.0 \pm 0.1^\circ\text{C}$, $\text{RH}=50\% \pm 5\%$).

Table 2. Results for measured distance errors (E_m): point-to-point measurement error for each distance and each angle of the scanned plate. The experiment was conducted in NRC-IIT metrology laboratory (controlled environment)²⁹.

Nominal Plate Distances from SUT (mm)	Nominal Distances from reference plate (mm)	Measurement Distance Error E_m (mm)				
		0° Vector 2	-40° Vector 1	40° Vector 3	-60° Vector 1	60° Vector 3
4112.7	D1 = 1505.411	-0.165	-0.132	-0.131	-0.112	-0.267
5607.7	D2 = 3000.641	-0.024	0.208	0.205	0.231	0.062
7106.7	D3 = 4500.085	-0.084	0.205	-0.069	0.565	-0.541
8606.6	D4 = 6000.074	-0.401	0.149	-0.691	0.178	-0.753

Figure 10. Block diagram summarizing the processing of the data from the SUT. R,T are the rotation and translation matrices respectively. Five sets of five intersection points are obtained.

In the course of the experiments, we discovered that the SUT laser scanner was not capable of scanning the same physical angle from one image to the next. Therefore, we had to re-align all the scanned 3D images with the 3D image from position 0 before starting the analysis. This is reflected in the block diagram of Figure 10. We are aware that this extra procedure adds on the uncertainty values. We are in the process of resolving this issue.

Table 3. Results for the measured distance errors (E_m): point-to-point measurement error for each distance and each angle of the scanned plate. The experiment was conducted in an office hall way (un-controlled environment).

Nominal Plate Distances from SUT	Nominal Distances from reference plate	Measurement Distance Error E_m (mm)				
(mm)	(mm)	0° Vector 2	-40° Vector 1	40° Vector 3	-60° Vector 1	60° Vector 3
6419.2	D1 = 1981.969	0.329	0.017	0.677	0.228	0.560
10655.0	D2 = 6218.191	-0.374	-1.087	0.480	-0.727	0.502
16482.2	D3 = 12045.348	-0.583	-1.022	0.759	-1.093	1.089
23232.5	D4 = 18.796.073	-0.509	-1.426	0.961	-1.604	1.959

In order to test the method and our laser scanner over a distance of 23 m, we performed the protocol in a hallway next to the metrology laboratory. The experiment was done during a week-end and the temperature was about $21.5^{\circ}\text{C} \pm 1^{\circ}\text{C}$ (RH was not verified). The results for E_m are given in Table 3. From those results, we see a systematic behavior in the errors as a function of distance and plate angle: positive values for D1, negative values for 0°, -40° and -60°, and, positive values for 40° and 60°. This behavior is not well reproduced in the results in the laboratory (see Table 2). More analysis will be required to fully understand the nature of the errors. Error propagation through the processing steps illustrated in Figure 9 and Figure 10 may reveal part of the answer.

Table 4. Standard deviations (STD_m) of the error after best-fit of a plane equation through the 3D data for each distance. The experiment was conducted in an office hall way (un-controlled environment).

Nominal Plate Distances from SUT	Position number	Standard deviations from a best-fit plane STD_m (mm)				
(mm)		0°	-40°	40°	-60°	60°
4437.5	0: reference	0.165	0.197	0.192	0.161	0.169
6419.2	1: used for D1	0.178	0.216	0.206	0.180	0.183
10655.0	2: used for D2	0.197	0.258	0.264	0.224	0.231
16482.2	3: used for D3	0.397	0.577	0.518	0.484	0.495
23232.5	4: used for D4	0.743	1.091	1.202	1.042	1.047

The standard deviations of the error (STD_m) after a best-fit on each plane generated from the scanned data are listed in Table 4. As mentioned earlier, the test surfaces of the plates are made of aluminum which has been treated using a special vapor blasting process. In a real situation (complex topology, weathering ...), the values listed on Table 4 will be different.

5. CONCLUSION

This paper presents a procedure to evaluate distance measurement uncertainty of medium range laser scanners (range between 2-100m). The procedure is based on the evaluation of Point-to-Point distance errors using custom made RTOs and a certified 3D laser tracker as a reference. This work is proposed as a possible protocol to the American Society for Testing and Materials (ASTM)-E57.02 3D Imaging Systems standards committee on test methods. Such a standard will address the aspect presented in this paper as well as many more quality parameters like lateral resolution, distance uncertainty, dynamic range etc.

The proposed protocol does not require that the location of the plates be positioned accurately. The method assumes that they can be measured with a laser tracker for each position. The experiment was conducted in both an environmentally controlled laboratory at NRC-IIT and in the building hallway. In the case of a SUT like the Surphaser® Model HS25X, such error is well within the measurement capability of the scanner. Therefore, a user can use the proposed protocol outlined in this paper to just check five targets (SMRs) every time a system needs to be checked against a manufacturer's specifications. This makes the proposed protocol faster, and more accurate. From the experimental results obtained, the

angle of a surface with respect to a given scanning angle range has an impact on the distance uncertainty of the laser scanner. A plate at 0° , $\pm 40^\circ$ and $\pm 60^\circ$ were used. The uncertainty resulting from best-fitting a plane equation through 3D scanned data taken on a plate at different distances shows the well known effect of increasing uncertainty with distance. Data on commercial products were provided for the sake of illustrating the proposed protocol.

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