Characterization of Triangulation-Based 3D Imaging Systems Using Certified Artifacts

Jean-Angelo Beraldin, Benjamin Carrier, David MacKinnon, and Luc Cournoyer

Abstract: A set of test procedures and certified artifacts to characterize the capability of short-range triangulation-based three-dimensional (3D) imaging systems are presented. The approach consists of scanning metallic and coated-glass certified artifacts in which the uncertainties in the associated characteristic reference values are smaller than the measurement uncertainties produced by the system under test (SUT). The artifacts were grouped on the same plate for portability. To define a set of test procedures that is practical, simple to perform and easy to understand, we utilized a terminology that is well-known in the manufacturing field, i.e., geometric dimensioning and tolerancing (GD&T). The National Research Council Portable Characterization Target (NRC-PCT) is specifically designed for the characterization of systems with depths of field from 50 mm to 500 mm. Tests were performed to validate the capability of the NRC-PCT. This paper presents these results, along with some basic information on 3D imaging systems.

1. Introduction

Advanced manufacturing technologies are now producing parts with complex surface shapes in a wide variety of materials and surface finishes [1, 2]. To ensure conformance between the designed part (intended) and the manufactured part (actual), it is necessary to understand and use the right dimensional inspection technologies. Today, optical non-contact equipment is used alongside more established contact dimensional measurement technologies for the inspection of manufactured parts, e.g. Coordinate Measuring Machines (CMMs) and Laser Trackers (LTs) [3].

This paper discusses 3D imaging systems that can acquire very dense point clouds made up of coordinates obtained by “probing” the visible surfaces of parts without making contact with them. The applications for 3D imaging technology have expanded considerably in the last 25 years and the number of players in this field has continued to increase, but internationally-recognized standardized procedures for characterization and verification of 3D imaging systems have not kept pace with the technological advancements. Users are left with the “burden” of sorting through company-specific data and creating their own set of specifications before using 3D imaging systems for their intended applications. This may appear to be sufficient in the short term, but it is not a strategy for the growth of the technology itself, let alone for solving metrology problems that involve complex assemblies that are often designed, manufactured and assembled on different continents. In fact, not all users are equipped to test systems in a systematic way, and companies often lack the on-site expertise to do that work.

Sections 2 and 3 of this paper briefly review the basic sensing principles of 3D imaging techniques. Regardless of the sensing method, best practice requires an independent means to ensure that the measurement uncertainty will meet the requirements for a given application. We present a set of test procedures and artifacts to characterize the capability of a 3D imaging system to accurately measure the geometric properties of an object’s surface. The approach consists of scanning certified artifacts in which the uncertainties of the associated characteristic reference values are much less than the measurement uncertainties produced by the system under test (SUT) under specified measurement conditions. All of the metallic and coated-glass artifacts selected for the characterization target were grouped on the same plate in a target case for portability, allowing us to propose the NRC portable characterization target (NRC-PCT) for short-range triangulation-based 3D imaging systems. These systems represent the bulk of optical technologies in use in manufacturing for objects that range in volumes from roughly 10 cm³ to 1 m³. To define a set of test procedures that is practical, simple to perform and easy to understand, we decided to use a terminology that is already well-known in the manufacturing field, i.e., geometric dimensioning and tolerancing (GD&T). This paper builds on previously-published work into artifact and GD&T based characterization of 3D imaging systems [4, 5].

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Sections 4 and 5 review standardization work in 3D imaging and GD&T, respectively. This is followed by a brief description of the NRC-PCT, which is constructed around GD&T-based metrics whose application is described in Sections 6 and 7. Section 8 provides results of tests performed in a special dimensional metrology laboratory to validate the capability of the NRC-PCT [6]. Section 9 discusses the NRC-PCT and other artifacts proposed in the literature, and Section 10 summarizes the key points presented in this paper.

2. Optical 3D Imaging Principles

Optical 3D imaging systems produce a digitization representation (i.e. a dense point cloud of X-Y-Z coordinates in a Cartesian coordinate system) of a surface with a given standoff distance, within a finite volume of interest, with a certain measurement uncertainty, and, with a known spatial resolution. These imaging systems are non-contact. They digitally capture not only the geometry of the visible surfaces of objects, but also an intensity image. Our main focus is on optical triangulation for which we summarize the intrinsic measurement uncertainty. The understanding of these basic principles allows us to devise test procedures and artifacts that can be used to characterize the performance of a given SUT. For example, 3D artifacts for triangulation-based systems may prove useless for time-of-flight 3D imaging systems.

2.1 Classifying Optical 3D Imaging Systems According to Measurement Principles

Optical 3D imaging systems can be classified according to their measurement principle, e.g. active versus passive methods, coherent versus direct light detection methods (see Fig. 1(a)), or surface-based versus volumetric, etc. Our discussion will center on active systems. These systems use lasers, low coherence sources (e.g. LEDs) or broad spectrum sources (e.g. halogen lamps) to artificially illuminate a surface using known patterns in order to acquire dense 3D images (usually more than a million coordinates in a matter of seconds) using triangulation, time-of-flight, or interferometric methods [7]. They typically operate with light sources in the spectral range from 400 nm to 1600 nm. Figure 1 depicts the three basic methods to optically probe a 3D surface and generate a 3D image.

Active 3D imaging systems provide the geometry of the surface of an object, even when the surface appears rather featureless to the naked eye or a photographic/video camera. Passive systems instead use light that is naturally present in a scene (unstructured illumination), surface texture (linked to surface reflectance) features and, sometimes, information that is known a priori to extract 3D data. Photogrammetry is the method of choice for passive systems [8].

Figure 1. Common non-contact optical 3D surface measurement methods for objects whose size is in the 1 mm to 10 km range: a) white light interferometry, b) light transit time using delay estimates, and, c) triangulation.

Figure 2. Classification of optical distance measurement techniques, a) according to the type of light detection technique, b) according to their depth uncertainty versus object size (sampling rate over 5000 3D coordinates per second, high signal-to-noise ratio, industrial-grade systems); MWI: Multiple-wavelength interferometry; ESPI: Electronic speckle pattern interferometry; AM: Amplitude modulation; AM-FM: Frequency modulation of light power; λ-FM: Optical frequency modulation (wavelength).
Interferometry (single/multiple wavelengths, white light) can be classified as a category of methods (see Fig. 1(a)). We must note that in interferometric systems, coherent detection is used (classification in Fig. 2(a)). This means that phase or frequency measurements of an optical beat signal derived from the processing of the light electric field is used to compute distance [7, 9, 10]. For light transit-time-base methods, light waves travel with a finite and constant velocity in a given medium; thus, the measurement of a time delay created by light traveling from a source to a reflective target surface and back to a light detector offers a convenient way to evaluate distance (see Fig. 1(b)). These systems are also known as time-of-flight (TOF), LIDAR or LADAR [11]. Light intensity modulation methods encompass pulsed-width (PW) modulation, amplitude-modulation (AM), frequency-modulation (FM), and pseudo-noise (PN) modulation. As illustrated on Fig. 1(c), triangulation exploits the law of cosines by constructing a triangle using an illumination direction (angle) aimed at a reflective surface and an observation direction (angle) at a known distance (base distance or baseline) from the illumination source. Triangulation and most commercial TOF systems are based on direct light intensity detection (signals proportional to the square of the electric field). For triangulation, the collection direction is separate from the projection direction (non-axial), creating a situation in which shadows appear as holes in 3D images. When an object has a complex topography with large valleys, ridges and step heights, light projected onto the surface does not necessarily reach the image sensor on the collection side. Focus and confocal methods use direct detection and they are sometimes included in triangulation methods even though measurements performed by these systems are axial (see Fig. 2(a)). This topic is beyond the scope of this paper, but details are available in [9]. Triangulation-based 3D imaging systems represent the bulk of optical technologies in use in manufacturing for objects roughly in a volume from 10 cm$^3$ to 1 m$^3$ and at acquisition rates above 5000 3D coordinates per second (see Fig. 2(b)).

### 2.2 Optical Triangulation

El-Hakim and Beraldin [12] summarized the depth measurement uncertainty by the standard deviation, $\delta_z$, for each class of 3D laser-based scanners when the effect of the light-material interaction is neglected. It is interesting to note that the uncertainty of many depth capture methods can be expressed by a single equation that depends on the signal-to-noise ratio ($SNR$ in terms of power ratio) when $SNR > 10$. The depth uncertainty has the following form,

$$\delta_z \approx K \frac{1}{\sqrt{SNR}}$$

where $K$ is a parameter that depends on the distance capture method. The $SNR$ is governed by the light source power and spectral content, detector sensitivity, distance to a surface, the surface material properties (opaque, Lambertian, specular, low-reflectivity, retro-reflective, curvature, translucency, etc.), and, the collecting lens diameter. With coherent detection, the $SNR$ is limited by the shot-noise-limited condition that is achieved by increasing the optical power of the reference signal. For very large $SNR$ and for rough surfaces (in relation to light wavelength), triangulation-based method performance as a function of depth uncertainty will be limited by speckle noise, which in turn depends on the speckle contrast, $C$. Speckle contrast is $C = 1$ for coherent illumination and $C < 1$ for partially incoherent illumination. As described in Häusler and Etlt [13] and with reference to Fig. 3(a)), the depth uncertainty is given by

$$\delta_z \approx \frac{C \lambda}{\sin \theta \sin u}$$

where $\lambda$ is the laser wavelength, $\theta$, the triangulation angle, and, $u$, the observation aperture. Fringe projection, with either a laser or a slide projector combined with a Halogen lamp, can also form the basis for triangulation-based 3D imaging systems. Implementation details appear in Jähne et al. [7] and depth uncertainty is given in Drouin and Beraldin [14].

When the principles illustrated in Fig. 1 are implemented, they yield a distance probe that can measure one coordinate at a time. To get dense point clouds of X-Y-Z coordinates, three basic scanning techniques are used. These scanning techniques are

#### 1. Single-Axis 3D Imaging Systems -
These systems use only one degree of freedom (DoF) in the motion between the system and the measured object to perform digitization. This motion can either be a translation or a rotation (see Fig. 3(b)). Spot scanning can be included here, although two orthogonal scanning axes are required [11],

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*Figure 3. Active triangulation, a) single point measurement, b) laser-line projection.*
2. Multi-Axis 3D Imaging Systems -
For these systems, any type of relative motion can be used between the system and the measured object to perform the digitization. They allow more than one DoF in motion. For example, a laser scanner is sometimes mounted on a 6-DoF articulated arm (not shown).

3. Static 3D Imaging Systems - These systems have a fixed origin and use neither moving parts nor relative movement between the scanner and the measured object [7, 14].

The result of such scanning processes yield either one 3D image per scan (case 1 and 3) or a series of profiles (case 2, e.g. system mounted on an articulated arm or photogrammetry is used to reposition these profiles in a unique coordinate system). Figure 4 illustrates some of the intermediate and final results of a typical scanning process.

3. Parameters to Characterize
To characterize all aspects of the SUT, three major categories of parameters must be compiled. These are the parameters provided by the manufacturer’s specifications, parameters calculated from the procedure being used, and parameters obtained from tests using certified artifacts, each with their known measurement uncertainty that is much lower than the uncertainty provided by the SUT. Figure 5 lists the parameters that characterize a 3D imaging system.

In this paper, the emphasis is placed on the parameters originating from the geometric properties of the artifacts chosen within the proposed NRC-PCT used for characterization and verification (the rightmost column in Fig. 5). We now review current standardization activities in 3D imaging.

4. Standardization Activities for 3D Imaging Systems (Optical)
The few guidelines and standards available for 3D imaging systems have emerged from the world of CMMs. ISO 10360 is an international series of standards that provide methods for the acceptance and re-verification of CMMs [15]. Parts 1 through 6 deal specifically with CMMs, but a part 7 was added to include CMMs with imaging probing systems. The VDI 2634 is devoted to acceptance and re-verification testing of optical non-contact 3D imaging systems, but is limited to optical non-contact 3D imaging systems that perform area scanning from a single viewpoint (case 3) as described above [16]. The VDI 2634 was written as an extension to the ISO 10360 so it drew heavily from CMM standards; however, 3D imaging systems utilize measurement principles that differ substantially from those of CMMs. For this reason, it may be tempting to select terminology and related analytical methods to match the 3D imaging system technologies employed. It is the opinion of the authors, however, that analytical methods and terminology should be driven by how the system is being used rather than by the underlying imaging technology. Obviously, there will be 3D imaging specific characteristics, but the core should be aligned with the intended use of the system, especially in manufacturing activities. Current efforts to better define standards for characterizing 3D imaging systems include the ASTM E57 committee [17] for medium and long-range systems and the ISO/CD 10360-8 working group (CMMs equipped with optical distance sensors) [15]. We are specifically concerned with the verification and characterization of 3D imaging systems in the short range (volumes from 10 cm$^3$ to 1 m$^3$) as mentioned in previous sections.

5. GD&T and Purpose-driven Evaluation
Companies seeking to implement short-range non-contact 3D imaging systems as part of their production process must decide in which
The lack of a universally accepted standard makes it difficult to select a system based on information provided by the manufacturer. The operating limits of a system should be obtained using standardized methods so that the manufacturer can provide characteristic values that mean something to the customer, e.g. in terms of specified tolerance limits.

If we know the specified tolerance limits to be assessed and have a method for quantifying the applicable operating limits of the 3D imaging system, then it is possible to

- determine whether the operating limits of the 3D imaging system are within the applicable specified tolerance limits with a suitable error margin,
- determine which 3D imaging system generates the smallest applicable operating limits, and,
- perform a cost-benefit analysis to determine which system provides the best return on investment.

The operating limits are highly dependent on how the measurement results were post-processed before they were calculated, so it is critical that published operating limits be accompanied by details about the post-processing method.

5.1 GD&T

The nomenclature used to describe various characterization metrics should have analogues in the world of manufacturing so that the quantity values used to evaluate a 3D imaging system can be associated with process metrics already in use. GD&T, documented in the ASME Y14.5 [18] and ASME Y14.5.1M [19], is a terminology commonly used to describe objects in terms of their geometry and dimensional tolerances from design to inspection. If, for example, the 3D imaging system has been purchased for the verification of these dimensions and tolerances, then it is critical to be able to determine how well the system performs these functions. The ISO has a set of standards similar to the ASME Y14.5 and Y14.5.1M, but those standards are spread over many documents rather than being encapsulated in only two. We, therefore, use nomenclature drawn from GD&T as described in ASME Y14.5 and Y14.5.1M to characterize a 3D imaging system.

5.2 Purpose-driven Analysis

A typical application of a 3D imaging system in an industrial environment is to assess whether the size, form, orientation, location, and profile of features on a work piece are within specified tolerance limits. These can be referred to as a conformance assessment as described in ISO 14253 [20]. These tolerance limits are usually defined by the designer to ensure the mechanical functionality of the work piece in an assembly. The manufacturing and inspection process must be selected according to the tolerance limits that need to be achieved. Figure 6 shows a subset of GD&T tolerance elements that need to be tested to characterize the capability of a 3D imaging system to provide accurate GD&T measurements.

Because a large percentage of short-range 3D imaging systems are deployed in a manufacturing environment, it is important to know the capability of the SUT to measure features associated with GD&T. Indeed, the terminology used in GD&T is what makes it possible to define an object with respect to its design, manufacturing process, and final inspection. The measurement system must be able to collect GD&T-compatible information about a workpiece in order to determine its geometric characteristics. The five properties listed above are evaluated for the SUT. In addition to being able to perform the characterization of a system, the use of GD&T vocabulary and associated tests will allow users to know how well these systems can meet the needs of different applications.

6. Characterization Based on Artifacts – Geometric Properties

Some of the test procedures presented in this paper are similar to those described in the VDI/VDE 2634 Part 2 [16] guidelines but are described here using a terminology linked to GD&T [18, 19]. Furthermore, these artifacts may be appropriate for a particular system and application, but may be totally impractical for other systems. Therefore, the NRC-PCT is specifically designed for the characterization of systems with depths of field (DOF), Fig. 8(b), from 50 mm to 500 mm.

We use artifacts certified to have known characteristic values and uncertainties. Although most of the artifacts selected were previously certified for particular characteristic values, these values are invalidated by the vapor-blasting process, so a precision CMM is used to recertify these artifacts. The measurement uncertainty is at least five times smaller than the measurement uncertainty obtained from measurements of the SUT, as recommended in the VDI/VDE 2634 Part 2 [16]. With these certified artifacts, it becomes possible to characterize the SUT by comparing the digitized results obtained for an artifact with the corresponding calibrated characteristic value. The reference values associated with the artifacts are obtained using calibrated systems that provide a better accuracy than the SUT. In the case of the geometric properties of the artifacts, each feature is obtained from measurements performed by a CMM giving us reference values for all of the artifacts on the NRC-PCT.

Artifacts are selected for the different tests based on their geometrical, optical and thermal properties. Indeed, the geometrical properties of the chosen artifacts must represent known features that make it possible to use GD&T-
The vapor-blasting operation consists of abrasive particles suspended in water that are propelled at high speed onto the artifact in order to change the surface finish. This operation changes the form and dimension of the artifact being vapor-blasted [21] so the reference values we use are those measured by the CMM after this operation.

From the CMM measurements we have performed on the NRC-PCT after vapor blasting, all the reference values are more accurate than the typical accuracy of 3D imaging systems that the PCT is designed for. For example, the flatness values of the different planes on the PCT vary from 1 to 7 µm and the circularity of the spheres vary from 1 to 3 µm. The measurements were performed with a Mitutoyo™ CMM Legex™ 9106 within an ISO 1 laboratory. According to the manufacturer’s specification sheet, the MPE (ISO 10360-2:2001) is (0.35 + L / 1000) µm and the MPE (ISO 10360-2:2001) is (0.45 µm). Considering that the longest length is 384 mm on the PCT, we anticipated that the contribution of the CMM to the length measurement uncertainty budget would be lower than 0.734 µm. Figure 7 shows a photograph of the NRC-PCT in (a) and in (b) the representation of the GD&T metrics.

Finally, these artifacts must have a low coefficient of thermal expansion (CTE) of the stainless steel ~ 17.3 ppm / °C, CTE of the glass ~ 8.5 ppm / °C) to avoid any deviation caused by possible changes in temperature during the test process. The artifacts are grouped on a composite plate having a low coefficient of thermal expansion (CTE of the carbon plate ~ 2 ppm / °C). The tests required for the characterization of the geometric properties are described in the following sections.

6.1 Size

Five tests are needed to determine the SUT’s capability to provide accurate size measurements. These tests are the diameter error on a sphere, the sphere-spacing error, the unidirectional plane-spacing error, the bidirectional plane-spacing error, and the angle error.

6.1.1 Diameter error

The diameter error, $E_d$, is the difference between the measured diameter, $d_m$, and the calibrated diameter, $d_c$, of that same sphere, obtained from CMM measurements,

$$E_d = d_m - d_c$$  \hspace{1cm} (3)

Eight vapor-blasted steel spheres are distributed over the NRC-PCT (see Fig. 7) to cover a maximum of the measurement volume of the SUT, and the diameter error is calculated for each sphere. The measured diameter is the diameter of the best-fit sphere fitted to the measured data points. The diameter error characteristic reported for the SUT is the largest value for all scanned spheres in all measurement orientations.

6.1.2 Sphere-spacing error

The sphere-spacing error, $E_{SS}$, is the difference between the measured distance, $l_{m,SS}$, between two sphere centers and the calibrated length, $l_{c,SS}$, of that same distance obtained from CMM measurements,

$$E_{SS} = l_{m,SS} - l_{c,SS}$$  \hspace{1cm} (4)

Using the eight vapor-blasted steel spheres on the NRC-PCT (Fig. 7), 28 combinations of sphere-spacing error can be calculated. The measured distance is obtained by the distance of two sphere centers best-fit on measured data with the radius constrained to the certified radius for each sphere. A radius-constrained sphere fit, in addition to converging faster, tends to generate smaller position errors because the convergence is limited to finding the sphere center. As a result, radially-constrained sphere fitting is preferred where the radius is not a factor of interest, as it was for diameter error. The sphere-spacing error characteristic reported for the SUT is the largest value of all length errors from all measurement orientations.

6.1.3 Unidirectional plane-spacing error

The unidirectional plane-spacing error $E_{UPS}$ is the difference between the measured distance, $l_{m,UPS}$, between two planes with same normal and the calibrated length, $l_{c,UPS}$, of that same distance obtained from CMM measurements,

$$E_{UPS} = l_{m,UPS} - l_{c,UPS}$$  \hspace{1cm} (5)

Nine vapor-blasted gage blocks of different lengths are mounted side-by-side on a reference plane (Fig. 7) and the unidirectional plane-spacing error is calculated for each gage block relative to the reference plane. For each measured plane, a best-fit plane, constrained parallel to the reference plane, is calculated and the distances between the reference plane and the plane on each gage block are compared to the certified lengths from CMM measurements. All gage blocks are positioned so that they are coplanar with the reference plane to within a level of uncertainty much less than the uncertainty associated with the SUT. The unidirectional plane-spacing error characteristic reported for the SUT is the largest value of all scanned length errors from all measurement orientations.

6.1.4 Bidirectional plane-spacing error

The bidirectional plane-spacing error, $E_{BPS}$, is the difference between the measured distance, $l_{m,BPS}$, between two planes with
opposite normal and the certified length, \(l_{\text{RPS}}\), of that same distance obtained from CMM measurements,

\[
E_{\text{RPS}} = l_{\text{m,RPS}} - l_{\text{RPS}}.
\] (6)

A single vapor-blasted steel gage block is used for this test (see Fig. 7). Note that this test can only be performed by multi-axis 3D imaging systems as defined in Section 2.2 because more than one DoF must be available to perform this test. On both opposite planes of the gage block, two best-fit planes are calculated with a parallelism constraint. The measured distance is the distance between those two planes. The bidirectional plane-spacing error characteristic reported for SUT is the largest value of all scanned length errors from all measurement orientations.

6.2.1. Flatness
The angle error, \(E_a\), is the difference between the measured angle, \(a_m\), from an orientated plane to a reference plane and the calibrated angle, \(a_c\), of that same angle obtained from CMM measurements,

\[
E_a = a_m - a_c.
\] (7)

Nine vapor-blasted steel angle blocks on a reference plane are used to perform this test (Fig. 7) and the angle error is calculated for each angle block relatively to the reference plane. The measured angle is the angle between a best-fit plane on the angle block and a best-fit plane on the reference plane. The angle error characteristic reported for the SUT is the largest value of all scanned angle errors from all measurement orientations.

6.2 Form
To know the ability of the SUT to provide accurate form measurements, two tests need to be performed. These tests are the flatness of a plane and the circularity of a sphere.

6.2.1. Flatness
The flatness deviation on a plane, \(F\), is the difference between the maximum and the minimum of the signed orthogonal distances, \(d_{\text{max,F}}\) and \(d_{\text{min,F}}\), from the measured points to the best-fit plane fitted to the measured points,

\[
F = d_{\text{max,F}} - d_{\text{min,F}}.
\] (8)

One vapor-blasted steel four-ways parallel and a chrome-coated optical flat are used to calculate the flatness metric (Fig. 7). The difference between the maximum and the minimum signed orthogonal distances (i.e. orthogonal to the best-fit element) from each point to the best-fit plane based on the least-squares fitting method is computed as the flatness deviation. The flatness characteristic reported for the SUT is the largest value of all scanned planes from all measurement orientations.

6.2.2 Circularity
The circularity deviation on a sphere \(R\) is the difference between the maximum and the minimum of the radial distances, \(r_{\text{max,R}}\) and \(r_{\text{min,R}}\), from the measured points to the best-fit sphere fitted to the measured points,

\[
R = r_{\text{max,R}} - r_{\text{min,R}}.
\] (9)

Eight vapor-blasted steel spheres (Fig. 7) are used to calculate circularity metric. The sphere diameters must not be constrained in the calculation of the fitted spheres. The difference between the maximum and the minimum of the radial distances from the points to the fitted sphere is computed as the circularity deviation. The circularity characteristic reported for the SUT is the largest value of all of the scanned spheres from all measurement orientations.

6.3 Orientation
To know the capability of the SUT to provide accurate orientation measurements from one feature to another, only one test, the angularity deviation, needs to be performed. ASME Y14.5-2009 [18] also describes parallelism and perpendicularity as orientation tolerance, but these two tolerances are particular angularity cases where the angle is either 0° or 90°. For the assessment of the capability of the SUT to provide orientation measurements, the angularity test is sufficient for characterization. This test is very similar to the flatness test. The difference is that the flatness test is not compared to a reference, while the angularity corresponds to a flatness deviation at a specific angle relative to a reference plane.

6.3.1 Angularity
The angularity deviation, \(A\), is the difference between the maximum and the minimum of the signed orthogonal distances, \(d_{\text{max,A}}\) and \(d_{\text{min,A}}\), from the measured points to a best-fitted plane having its orientation fixed at the certified angle of that plane relative to the reference plane,

\[
A = d_{\text{max,A}} - d_{\text{min,A}}.
\] (10)

Nine vapor-blasted steel angle gauge blocks mounted side-by-side on a reference plane are used to perform this test (Fig. 7), and the angularity deviation is calculated for each angle block. The difference between the maximum and the minimum of the signed orthogonal distances from the points to the fitted plate constrained in angle is computed as the angularity deviation of the plane. The angularity characteristic reported for the SUT is the largest deviation value for any of the angle block measurements for only the orientations where the NRC-PCT is perpendicular to the measuring axis.

6.4 Location
To determine the SUT’s capability to provide accurate location measurements, three tests must be performed. These tests are the sphere position error, the corner position error and the hole position error. According to the ASME Y14.5-2009 [18], there are two ways to represent the position of a feature. We may want to know the position of the surface of a feature, or know the position of the resolved geometry (point, axis or plane) of the envelope. In our case, because the form aspect is analyzed separately in the form and profile section, we will use the position of the resolved geometry of the feature to be analyzed. This standard also provides the opportunity to apply different positioning bonuses depending on the dimension value of the positioned feature, which complicates the analysis. In our case, all the analysis will be made regardless of features size (RFS), which does not imply the dimensions of the features to verify because the dimensions are also analyzed separately. The RFS case also represents
the most restrictive case of the positioning analysis because no bonus can be applied to the feature, ensuring that this represents the worst case scenario and giving us characterization values that represent the limits of the SUT. The RFS case is also the easiest one to analyze. In what follows, an alignment A-B-C is made from the three vertices of the three small pyramids (according to the GD&T metric representation diagram), and the three locations errors are computed in the coordinate system.

6.4. Location

6.4.1 Sphere position error

The sphere position error, $L_{\text{sphere}}$, is the distance between the center of a best-fit sphere $(x_{m,\text{sphere}}, y_{m,\text{sphere}}, z_{m,\text{sphere}})$ and the certified position of that same sphere $(x_{c,\text{sphere}}, y_{c,\text{sphere}}, z_{c,\text{sphere}})$ obtained from CMM measurements,

$$L_{\text{sphere}} = \sqrt{(x_{m,\text{sphere}} - x_{c,\text{sphere}})^2 + (y_{m,\text{sphere}} - y_{c,\text{sphere}})^2 + (z_{m,\text{sphere}} - z_{c,\text{sphere}})^2}. \quad (11)$$

Eight vapor-blasted steel spheres are used to perform this test (Fig. 7) and the sphere position error is calculated for each sphere on the NRC-PCT. The sphere position error characteristic reported for the SUT is the largest value of all the sphere position errors from all of the measurement orientations.

6.4.2 Corner position error

The corner position error, $L_{\text{corner}}$, is the distance between a corner position $(x_{m,\text{corner}}, y_{m,\text{corner}}, z_{m,\text{corner}})$ generated by the intersection of three best-fit planes measured by the 3D imaging system and the certified position of that same corner $(x_{c,\text{corner}}, y_{c,\text{corner}}, z_{c,\text{corner}})$ obtained from CMM measurements,

$$L_{\text{corner}} = \sqrt{(x_{m,\text{corner}} - x_{c,\text{corner}})^2 + (y_{m,\text{corner}} - y_{c,\text{corner}})^2 + (z_{m,\text{corner}} - z_{c,\text{corner}})^2}. \quad (12)$$

Five vapor-blasted steel pyramids are used for this test (Fig. 7), and the corner position error is calculated for each corner on the NRC-PCT. For each measured corner, three best-fit planes are calculated from the original data points, and the position of the intersection of these three planes is calculated and compared to the reference position of that corner. The corner position error characteristic reported for the SUT is the largest value of all the corner position errors from all of the measurement orientations.

6.4.3 Hole position error

The hole position error, $L_{\text{hole}}$, is the distance between a hole center position $(x_{m,\text{hole}}, y_{m,\text{hole}}, z_{m,\text{hole}})$ generated by the intersection of its axis and the plane on which is located the hole measured by the 3D imaging system and the certified position of that same hole $(x_{c,\text{hole}}, y_{c,\text{hole}}, z_{c,\text{hole}})$ obtained from CMM measurements,

$$L_{\text{hole}} = \sqrt{(x_{m,\text{hole}} - x_{c,\text{hole}})^2 + (y_{m,\text{hole}} - y_{c,\text{hole}})^2 + (z_{m,\text{hole}} - z_{c,\text{hole}})^2}. \quad (13)$$

A vapor blasted predrilled steel 123-block is used for this test (Fig. 7), and the hole position error is calculated for this hole. Note that this test may be impossible to do with static and single-axis systems as defined in Section 2.2, depending on the orientation of the NRC-PCT. In that case, results are computed each time it will be possible to do so. For the measured hole, a best-fit plane and a best-fit cylinder are calculated from the original data points. The position of the intersection of the axis of the cylinder and the plane is calculated and compared to its reference position. The hole position error characteristic reported for the SUT is the largest value of all hole position errors from all of the measurement orientations.

6.5 Profile

To know the capability of the SUT to provide accurate surface profile measurements, only one test, surface profile deviation on a freeform object, needs to be performed. Note that this characteristic is closely related to the form characteristic; however, according to the ASME Y14.5-2009 [18], this tolerance is more complete because it can control, at the same time, the form, dimension, localization and orientation of a feature. That is why we analyze this metric separately.

6.5.1 Surface profile

The surface profile, $P$, is the difference between the maximum and the minimum of the signed orthogonal distances, $d_{\text{max},P}$ and, $d_{\text{min},P}$, from the measured points to a best-fit surface fitted to the measured points,

$$P = d_{\text{max},P} - d_{\text{min},P}. \quad (14)$$

A freeform surface is used for this test (Fig. 7). The reference surface corresponds to a surface generated by a point cloud obtained by a CMM. The difference between the maximum and the minimum signed orthogonal distances from the measured points to the fitted reference surface is computed as the surface profile. The surface profile characteristic reported for the SUT is the largest value of all scanned surfaces from all of the measurement orientations.

7. Measurement Procedure

Before we perform each test presented in this paper, some precautions must be taken. First, the NRC-PCT and the SUT must be allowed to reach thermal stability with respect to the atmospheric conditions where the tests will be done, ideally in a controlled temperature laboratory maintained at 20 °C as stipulated by ISO 1 [22]. At least 12 hours should be allowed for thermal stabilization. In the case where the tests cannot be done at 20 °C, the temperature of the tests should be reported as well as any thermal compensation that was applied. Also, the NRC-PCT and the SUT must be mounted properly to avoid any deformation or vibration that may affect the measurement process. To obtain each characterization parameter, the NRC-PCT should be measured in seven orientations. Depending on the SUT, these orientations may be obtained by positioning either the system or the NRC-PCT, using the configuration that is the easiest to achieve and provides the most stability. The seven orientations are presented in Fig. 8(a). There are three positions along the longest axis of the measuring volume at three different standoff distances (Fig. 8(b)) defined as the minimum (near) (1), median (mid) (2) and maximum (far) (3) distance. Another position is on the axis perpendicular to the first axis at a median standoff distance (4). The plate is also orientated on two of the body diagonals of the measuring volume (5 and 6). Finally, it is orientated 30° from position number 2 (7).

8. Some Tests Results

The NRC-PCT shown in Fig. 7 was used to test different 3D imaging systems with the procedures detailed in Section 6 and 7. In this example and with reference to Section 2.2, we use SUT A to refer to a
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Table 1 shows manufacturer specifications (rounded values for anonymity) of the systems evaluated in this experiment. The intent of the test results presented here is not to prove that one category of system is better than another, but simply to illustrate the characterization process.

For SUT A and SUT B, the NRC-PCT was digitized in the seven recommended orientations, and for each characterization metric the largest value was kept for this metric (Section 6). For SUT C, because it is a multi-axis system, the different orientations become irrelevant because the system already performs measurements in many different orientations. For SUT C, characterization metrics are obtained from only one pose of the NRC-PCT. Figure 9 shows an example setup for the digitization of the NRC-PCT with an example of scan results.

From the scans, it was possible to calculate the characterization parameters for all three systems (SUT). There were a few tests where it was impossible, for two of the systems, to obtain the metric value. This is the case for the bidirectional plane-spacing error because only multi-axis systems can perform the measurement. The location category of tolerances was also not computed for SUT A and B because the fields of view of the tested systems were too small to digitize all of the required datum features to properly calculate the location errors. Figure 10 shows the values for all characterization metrics that represent the limit of the SUTs to perform the corresponding measurement.

For the form parameters, it is also possible to accompany the characterization metric value with a color-coded representation of the deviation to know the behavior of the system, i.e. if the deviations are completely random, or if an error pattern is present. Figure 11 shows the flatness deviation on the 4-ways parallel for the three SUTs using color-coded errors with respect to a plane fit. For example, a bow in the deviation is apparent with SUT A (see Fig. 11(a)). A wave structure appears with SUT B (see Fig. 11(b)). For SUT C, the deviation errors appear random in nature (see Fig. 11(c)).

As can be seen in Table 1, the manufacturers specifications for resolution and accuracy cannot be used to assess the performance of a system in terms of GD&T related tolerance. Thus, having characterization parameters for a specific metric related to GD&T makes it possible to easily assess whether the SUT can perform the inspection task it is called upon to verify.

### Table 1. Manufacturer specifications for three SUTs, see Figure 8(b) for some definitions.

<table>
<thead>
<tr>
<th>SUT</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standoff distance</td>
<td>375 mm</td>
<td>200 mm</td>
<td>300 mm</td>
</tr>
<tr>
<td>Depth of field</td>
<td>75 mm</td>
<td>400 mm</td>
<td>150 mm</td>
</tr>
<tr>
<td>Resolution</td>
<td>N/A</td>
<td>0.015 mm</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.4 mm</td>
<td>N/A</td>
<td>0.05 mm</td>
</tr>
<tr>
<td>Near FOV</td>
<td>10 mm</td>
<td>150 mm</td>
<td>200 mm</td>
</tr>
<tr>
<td>Far FOV</td>
<td>100 mm</td>
<td>400 mm</td>
<td>200 mm</td>
</tr>
</tbody>
</table>

N/A: not applicable

**Figure 8.** a) Recommended orientations of the NRC-PCT for digitization within the SUT volumetric DOF, b) Graphical representation on a plane of terms used to describe 3D imaging systems.

**Figure 9.** Digitization of the NRC-PCT in a temperature controlled laboratory, a) photograph of one of the arrangements, b) rendering showing the scan result in terms of a point cloud with laser intensity mapped on each 3D point.

static 3D imaging system, SUT B to refer to a single-axis 3D imaging system, and SUT C to refer to a multi-axis 3D imaging system.
9. Discussion
In its current version, the NRC-PCT is specifically designed for the characterization of short-range systems (with a DOF from 50 mm to 500 mm as per Fig. 8(b)) that includes, most of the time, triangulation-based 3D imaging techniques. The low-cost artifacts selected provide a clearly-defined set of procedures for generating characteristic values using these artifacts. Some systems with small DOFs, however, may involve some rework on the NRC-PCT.

GD&T was identified as a universal terminology, making it possible to communicate all the geometric information concerning a part in either the design stage, manufacturing stage, inspection stage, or in the reverse engineering process. At the moment, we are the only group proposing this approach for 3D imaging systems. This change comes from our experience with other artifacts purchased or designed and built at NRC (see Fig. 12). This particular approach based on artifacts similar to those on Fig. 12(a), is the customary way of benchmarking a 3D imaging system in the literature [23-27]. Some have tested, and are using, shapes more like those compatible with the VDI 2634 [28], or use more organic shapes [3, 26, 29, 30].

We must note that the characterization of 3D imaging systems does not consist only of the system’s capability to measure geometric properties. To fully characterize a 3D imaging system, we must also characterize the External Frame of Reference (EFOR), the mathematic model fidelity used in the fitting calculation, the resolution properties, and the optical properties of the surfaces of the objects that the SUT can measure (Fig. 5). We also need to add the parameters given by the manufacturer’s specifications, and the parameters pertaining to the measurement procedure used during the tests.

These tests are also proposed as a basis for “Best Practice,” which we hope will lead in the future to internationally-accepted standardized methods for the characterization of 3D imaging systems. Tests proposed for use with the NRC-PCT represent most of the different aspects of GD&T, and thus make it possible to determine the ability of a 3D imaging system to measure features on a part or an artifact that can be tolerated.

10. Conclusions
We have presented the NRC portable characterization target (PCT) for short-range triangulation-based 3D imaging systems characterization (DOF from 50 mm to 500 mm). The tests we have described make it possible to assess the capability of 3D imaging systems to measure geometric properties on certified artifacts. Geometric properties tests are described in this paper using terminology taken from the ASME Y14.5-2009 [18] for GD&T. The GD&T-related terminology is applied to 3D imaging systems characterization for simplicity, because users from the manufacturing field already know this terminology. Furthermore, this choice will make system characterization

Figure 10. Characterization metric value for the three SUTs evaluated in terms of the form, the size, the orientation, and the location. The characterization metric value units used on the vertical axis are indicated below each column.

Figure 11. Color-coded flatness deviation on the 4-ways parallel for the three SUTs, a) a bow is evident in SUT A (color scale: -0.08 mm to 0.08 mm), b) waves appear with SUT B (color scale: -0.12 mm to 0.12 mm), c) for SUT C, the deviation errors appear random in nature (color scale: -0.03 mm to 0.03 mm).

Figure 12. 3D artifacts used at NRC in recent history, a) certified artifacts, b) low-cost portable artifacts for intercomparison amongst 3D imaging systems.
relevant to real life applications, and choosing a system for a specific application becomes more intuitive.

The NRC-PCT represents a much larger work than what has been presented in this paper. The remaining characterization parameters, which relate to mathematic model fidelity in fitting calculation, external frame of reference (EFOR) properties, optical properties and resolution properties, will be presented in future papers. The NRC will also organize an intercomparison protocol soon. This will validate the use of the PCT for characterization, and will allow users to obtain characterization values for systems that will be part of this study. Finally, the geometric properties tests presented here will be adapted in the near future to make the characterization tests compatible with ISO standards for GD&T.

11. References