Status of the NIST 3D Imaging System Performance Evaluation Facility *

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ABSTRACT

This paper presents the status of an indoor artifact-based Performance Evaluation Facility at the National Institute of Standards and Technology (NIST) for 3D imaging systems, a terminology pre-standard, and a summary of the ranging protocol pre-standard. The indoor facility will be used to develop test protocols and performance metrics for the evaluation of terrestrial 3D imaging systems. The NIST facility was initiated in response to a workshop which was held at NIST in 2003 to determine future efforts needed to standardize 3D imaging system testing and reporting and to assess the need for a neutral performance evaluation facility. Three additional workshops have since been held at NIST with the most recent on March 2–3, 2006. These workshops provided further guidance in defining priorities and in identifying the types of measurements that are of most interest to the terrestrial scanning community. The two pre-standards were developed based on feedback from the workshops.

1. INTRODUCTION

Although the technology for most 3D imaging systems has existed for several decades, the use of these instruments, has only in the past 10 years become more established or accepted and is still considered an emerging technology in many industries. In this same time span, the technology for 3D imaging systems has experienced significant advancements. However, there are still no standard test protocols for evaluating the performance of terrestrial 3D imaging systems and assessing the accuracy their derived output such as 3D models, volumes, and geometric dimensions. This lack of standard test methods is inhibiting a wider market acceptance of these systems not only in the construction sector but also in the manufacturing and transportation sectors. Standard test methods for the performance evaluation and use of 3D imaging systems will provide a basis for fair comparisons of such systems, reduce the confusion with regards to terminology, and increase user confidence in these systems.

3D imaging systems are used to rapidly capture (thousands of measurements per second) 3D information of a scene or object. This information is often provided in the form of point clouds with associated color and intensity data. The systems include laser scanners, laser radars, 3D optical scanners, 3D range cameras, and 3D flash LADARs (laser detection and ranging). Sub-classes of these systems of particular interest include those that are ground-based and are capable of capturing a scene that is on the order of a large capital project such as a process plant, construction site, building, or a bridge.

Between 2003 and 2006, four workshops have been held at the National Institute of Standards and Technology (NIST) to address the need for standard methods for the performance evaluation of 3D imaging systems [1, 2]. From the first workshop, there was a recognized need for a neutral facility for performance evaluation of 3D imaging systems, standard definitions of commonly used terms, and standardization of test protocols. It was also clear that a single facility would not be sufficient to evaluate the wide range of available systems. At a minimum, three types of facilities were foreseen as necessary: a small indoor facility, a medium range (50 m to 60 m long) facility, and an outdoor facility.

Based on the feedback from these workshops, an indoor, artifact-based performance evaluation facility for 3D imaging systems was initiated at NIST. At the last workshop, held on March 2-3, 2006, a terminology pre-standard and a ranging protocol pre-standard were presented for discussion and comment. The status of the indoor, artifact-based facility and a summary of both the terminology and ranging protocol pre-standards are presented in this paper.

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2. INDOOR ARTIFACT-BASED FACILITY

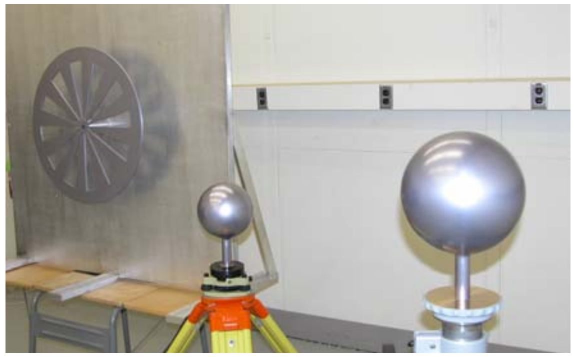
The indoor facility at NIST will primarily be used to develop test protocols and performance metrics for 3D imaging systems. The facility is 17 m (L) by 5 m (W) by 4 m (H) and is shown in Fig. 1. The facility is not temperature controlled, however, the facility environment is monitored using six temperature sensors and two humidity sensors. Over a period of about two months, the average temperature in the facility was 20.01 ºC (std. dev. = 0.21 ºC) and the humidity was 23 % (std. dev. = 7 %). The temperature in the facility appears to be relatively stable; however, the humidity varied from a minimum of 9 % to a maximum of 43 %.

Figure 1. Artifact-based evaluation facility.

Several prototype artifacts have been or are being fabricated for use in the facility – two aluminum spheres (152 mm and 203 mm diameter), a stair artifact, a slotted disc artifact, four 152 mm SMRs (spherically mounted retroreflectors), and a 3 m ball bar. The spheres, stair artifact, and slotted disc are shown in Fig. 2. Also, shown in Fig. 2 is a multi-reflectivity target.

The stair artifact consists of 30 steps with the step height varying from 1 mm to 30 mm in 1 mm increments. The slotted disc artifact is based on the artifact that was developed by Wolfgang Böehler [3]. This artifact was modified so that it is larger, circular, with the angles between the slots adjustable from 0º to 15º, and the distance between the disc and the back plane is variable from 25 mm to 254 mm in 25 mm increments. Both the stair and slotted disc artifacts can be used for quick and relatively easy qualitative evaluations of the differences in resolution between instruments. Efforts to develop quantitative measures using these artifacts will be investigated in the future. Some initial scans of these artifacts are shown in Fig. 3.

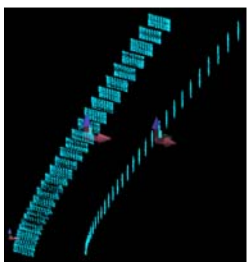
a. Stair artifact
(675 x 465 x 125) mm



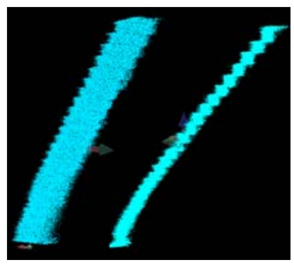
b. Slotted disc artifact and two anodized
aluminum spheres

c. Multi-reflectivity target
(457 x 457) mm

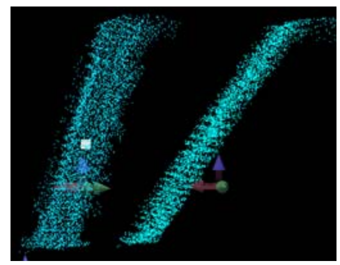
Figure 2. Prototype artifacts.



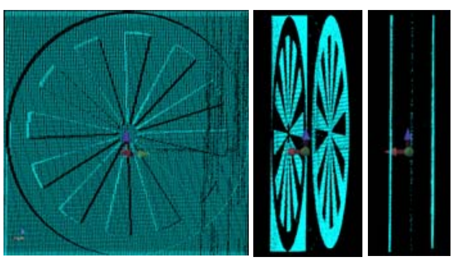
a.



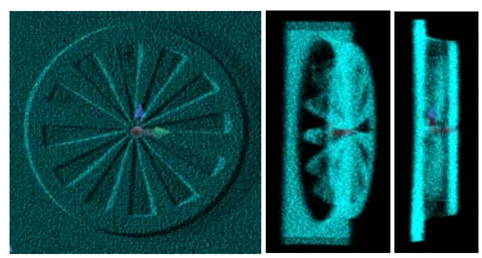
b.



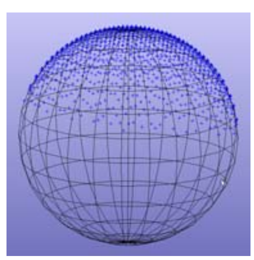
c.



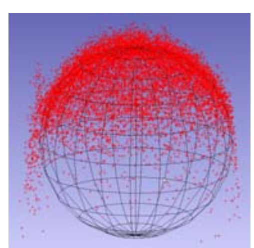
a.



b.



a.



b.

Figure 3. Initial scans of the stair artifact (upper set of images), the slotted disc artifact (middle set of images), and 203 mm sphere (lower set of images). Images a, b, and c were obtained using three different instruments.

The intent behind the sphere artifacts and the SMRs is to evaluate sphere fitting algorithms and to determine the uncertainty due to registration. Although sphere fitting algorithms are well understood, initial experiments at NIST showed variation in the determination of both the sphere center and radius using various algorithms to fit the data from the 3D imaging systems [4]. A schematic of the 3 m ball bar is shown in Fig. 4. The intent behind the ball bar is to use it in the field as a quick verification that an instrument is functioning within the manufacturer's specifications.

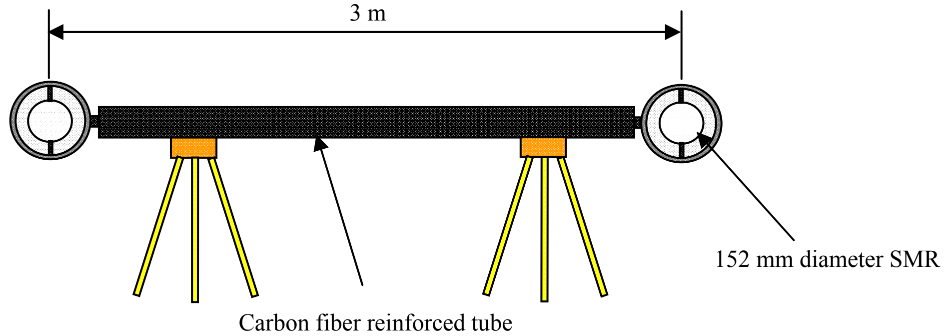


Figure 4. Schematic of 3 m ball bar.

In addition to the 457 mm x 457 mm, multi-reflectance target shown in Fig. 2c, other planar targets having corresponding reflectivities of ≈ 2 %, ≈ 22 %, ≈ 45 %, ≈ 75 % and ≈ 99 % for wavelengths between 250 nm and 2500 nm were procured. These targets have dimensions of 610 mm x 610 mm. A 1 m x 1 m target with a reflectivity of ≈ 98 % was also obtained. These targets will be used to test the ranging protocol in order to determine the appropriate target size and the practicality and feasibility of the specified procedures.

Other equipment in the facility include a rotation stage with a 4.448 kN (1000 lb) load capacity and four commercial 3D imaging systems. Another piece of equipment that will be necessary is a linear stage to help develop a protocol for evaluating the resolution of 3D imaging systems.

In addition to the small, indoor, artifact-based facility, there is another indoor facility† available at NIST that can provide reference measurements with an uncertainty (k=2) of 10 µm ± 0.5 µm/m (10 µm ± 0.5 ppm). This facility would fall under the medium range facility mentioned in Section 1. The facility is temperature and humidity controlled, and the barometric pressure is monitored. A rail system is used to position the targets up to a maximum distance of 61 m. Other artifacts available for use in this facility are 102 mm (4 in) diameter titanium spheres and 102 mm (4 in) diameter SMRs.

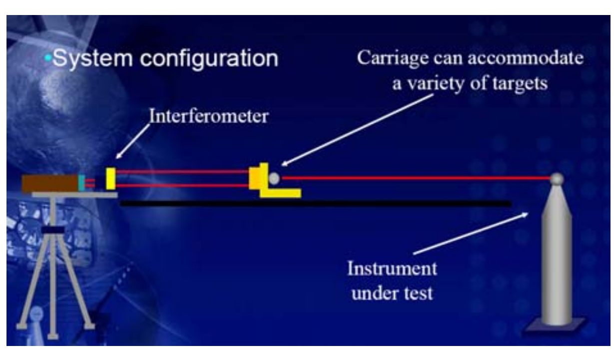


Figure 5. NIST's Indoor 1D Ranging Facility (Courtesy of S. Phillips, NIST)

† For more information about this facility, please contact Dan Sawyer, Daniel.sawyer@nist.gov.

Upcoming efforts planned for the artifact-based facility include evaluating and refining NIST-developed sphere fitting algorithms and determining the uncertainty resulting from the registration process using spheres.

3. TERMINOLOGY PRE-STANDARD

Definitions for common terms such as accuracy, systematic error, uncertainty, etc. have been adopted by standards developing organizations such as ISO and ASTM. No attempt will be made to change these definitions, and the definitions in those documents will be referenced as necessary. However, there are no standard definitions for some of the terminology that is commonly used by the 3D imaging community. Some of these terms and their suggested definitions are presented in this section. Terms that have asterisks require further consideration. An *issues* section follows each of these terms' definitions and contains questions or concerns that were raised by the workshop participants.

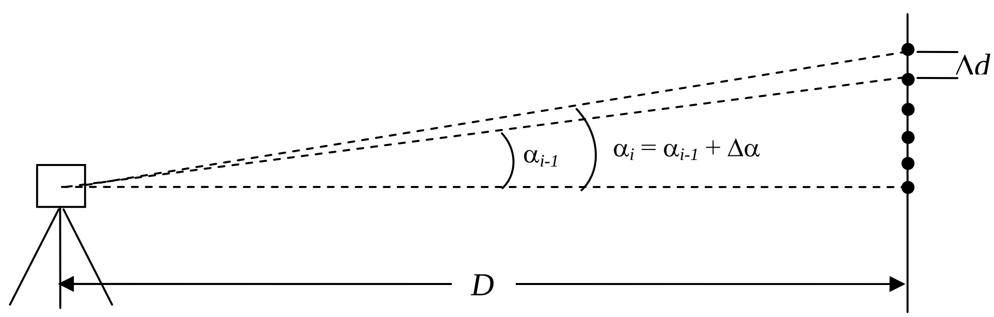
3D Imaging System*

A three-dimensional (3D) imaging system is an indicating instrument that is used to rapidly measure (on the order of thousands of measurements per second or faster) the range and bearing to and/or the 3D coordinates of points on an object or within a scene. The information gathered by a 3D imaging system is provided in the form of "point clouds" with color and intensity data often associated with each point within the cloud. Such systems include laser scanners, 3D optical scanners, 3D range cameras, LADARs, and 3D flash LADARs.

***Issues**: Care has to be taken when identifying which systems are to be included or excluded. Should photogrammetry be included/excluded? What about medical and short range imaging systems? Suggest rewording the sentence "These systems include laser scanners, 3D optical scanners, 3D range cameras, LADARs, and 3D flash LADARs." to "These systems include but are not limited to laser scanners, 3D optical scanners, 3D range cameras, LADARs, and 3D flash LADARs."*

Angular Increment

For a scanning instrument, the angular increment is the angle between contiguous measurements, $\Delta\alpha$, where $\Delta\alpha = \alpha_i - \alpha_{i-1}$, in either the horizontal or vertical direction. The angular increment is also known as the angle step size.



Distance between points = $\Delta d \approx D\,(1 + \tan^2 \alpha)\,\Delta\alpha$

This value, specified by the instrument manufacturer, is typically a minimum value, and the achievable point density may be inferred from this value (smaller angular increment results in a denser point cloud). The angular increment can be used to determine the distance between contiguous pixels or points, Δd, as shown above.

For a scan, the angular increment is often set equal in both the horizontal and vertical directions, and the value cannot be changed during a scan.

Angular resolution - See *Resolution*

Control points

Control points are visible or recoverable reference points common to both an independent source having higher accuracy and the product itself (point-cloud). An example of a recoverable reference point is the center of a sphere, while not visible, it can be obtained by processing suitable data. Control points are occasionally referred to as fiduciaries.

Control points may be used to:

- register two or more point clouds into a common reference coordinate system
- infer the accuracy of the derived output of a 3D imaging system.

  Example: Controls points are designated in a scan region and the locations of these control points (reference locations) are obtained by an instrument (such as a total station) of higher accuracy than the 3D imaging system used. The distances between any two of these control points (reference distances) can be calculated using the reference locations. Similarly, the distances between corresponding control points (measured distances) in the point cloud or model can also be calculated using the data obtained by the 3D imaging system. The differences between the measured and reference distances or the errors may be used to infer the accuracy of the point cloud or model. However, the errors are only known at the control points and may or may not be representative of the entire point cloud or model.

First return

The first return is the first reflected signal that is detected by the 3D imaging system for a given sampling position (i.e., azimuth and elevation angle).

Flash LADAR

A 3D imaging system comprised of a broad field illumination source [commonly a laser, but for close proximity it can be a bank of LEDs (light emitting diodes)] and a focal plane array (FPA) detector, in which the range image is acquired simultaneously in one burst. This can result in high frame rates (on the order of 30 frames per second or faster) which is critical for real time applications.

Frame*

A frame is equivalent to a region of interest where data is to be acquired. The size of the frame is generally user specified with the maximum size of a frame equivalent to the field-of-view (FOV) of the instrument.

***Issues**: The term frame is often used to refer to a coordinate system – suggest using a different term. Consider the concept an area or volume of interest?*

Frame Rate

The frame rate is the number of frames that can be acquired per second. For example, if 10 frames could be acquired in one second, the frame rate would be 10 Hz. This metric is generally applicable to real-time systems such as flash LADARs, since most commercial scanning 3D imaging systems have update rates on the order of minutes and are dependent on the laser pulse repetition rate, selected FOV, and selected angular increment. However, for non-real time instruments, knowledge of the frame rate is useful when comparing instruments since a higher frame rate could mean increased productivity.

In the case of non-real time systems, an appropriate description of the frame rate should include the time, FOV, and angular increment. For example, "the time to acquire a frame for a FOV of 360° x 90°, at an angular increment of 0.2° (horizontal and vertical) is 180 s." Note that the frame rate for a FOV of 90° x 360°, at an angular increment of 0.2° (horizontal and vertical) may be different if the mechanical speeds of the horizontal and vertical movements are different.

Instrument Center

The instrument center is the point within or on the surface of an instrument from which all instrument measurements are referenced, i.e., instrument origin (0, 0, 0).

Last return

The last return is the last reflected signal that is detected by the 3D imaging system for a given sampling position (i.e., azimuth and elevation angle).

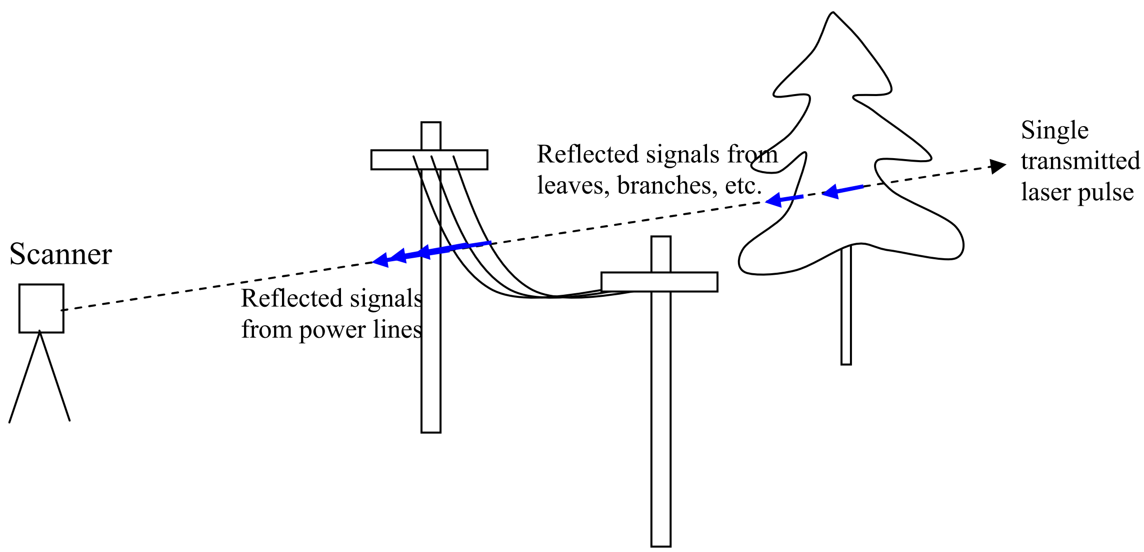
Mixed Pixels*

Mixed pixels or phantom points are caused by multiple returns. When a laser beam hits the edge of an object, the beam is split and part of it is reflected by the object and the other part is reflected by another object beyond the first object (see multiple returns). Typically, the reported range measurement in such a case is the average of the two range measurements and would, therefore, fall between the ranges to the two objects; hence, recording a point that does not exist and is referred to as a mixed pixel or phantom point.

***Issues**: Separate out the term "phantom points" as phantom points could be outliers. There are methods to remove mixed pixels but there are no well defined ones to remove phantom points because the sources of phantom points are not always known.*

Multiple returns

Multiple returns occur when the laser beam hits multiple objects separated in range. When this occurs, the beam is split and multiple signals are detected by the 3D imaging system, see figure below.



Point Cloud

A point cloud is a collection of 3D points, frequently numbering in the hundreds of thousands, obtained using a 3D imaging system.

Point Density*

Point density is the number of points per unit area at a specified range.

Example:

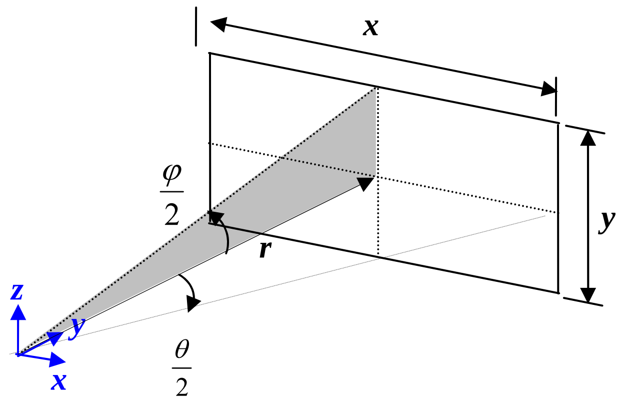
Point density at distance $r = \dfrac{a \times b}{x \times y}$

$x = 2 \times r \tan\left(\dfrac{\theta}{2}\right)$, $y = 2 \times r \tan\left(\dfrac{\varphi}{2}\right)$

a = nominal number of points in row = $\dfrac{\theta}{\Delta\theta} + 1$

b = nominal number of points in a column = $\dfrac{\varphi}{\Delta\varphi} + 1$

θ, φ = user specified field-of-view for a scan



$\Delta\theta, \Delta\varphi$ = angular increment in the horizontal and vertical directions, respectively.

Suggested r: 20 m, 50 m, and 100 m

Issues*: Consider row/line and column point spacing and report both values individually instead of points per unit area. Point density is dependent on beam spot size – what happens when beam spot size on an object is large? Other possible terms instead of point density are "cloud point density", "captured point density", and "displayed point density". Should point density be decoupled from angular resolution?*

Registration

Registration involves determining a set of rigid body transformations and applying those transformations to a data set to transform that set into another reference frame or into a global reference frame. Registration is required when two or more point clouds are obtained with each point cloud having its own frame of reference or local reference frame.

Registration Error

Local registration error: deviation from spatial agreement of registered point clouds at a location in an overlap region.

Global registration error: combination of local registration errors based on a vector norm such as RMS $\left(\sqrt{\dfrac{\sum e^2}{n}}\right)$.

Resolution*

Range or depth resolution: The smallest distance or separation, in range or depth, between two distinct objects that can be detected in a single scan.

Horizontal resolution: The smallest horizontal distance or separation between two distinct objects that can be detected in a single scan at a specified distance from the instrument.

For example, given a statement "The instrument has a horizontal resolution of 30 mm at 100 m." A user may infer that two objects, located at a maximum distance of 100 m from the instrument, are distinguishable if they are separated by 30 mm, at a minimum.

To eliminate the need to associate the horizontal resolution with a given distance, a *horizontal angular resolution* may be specified. The horizontal angular resolution will be based on the horizontal resolution.

For example, given a horizontal resolution of 30 mm at 100 m, the horizontal angular resolution is equal to

$$\arctan\left(\frac{30}{100 \times 1000}\right) = 0.017^{\mathrm{o}}$$

It is suggested that several angular resolution values be calculated based on horizontal resolutions at various distances from the instrument and that the horizontal resolution be, conservatively, specified as the largest value.

For example, given the following information,

$$\text{horiz. resolution of 14 mm at 50 m} \Rightarrow \text{angular resolution} = \arctan\left(\frac{14}{50000}\right) = 0.016^{\mathrm{o}}$$

$$\text{horiz. resolution of 29 mm at 100 m} \Rightarrow \text{angular resolution} = \arctan\left(\frac{29}{100000}\right) = 0.017^{\mathrm{o}}$$

$$\text{horiz. resolution of 49 mm at 150 m} \Rightarrow \text{angular resolution} = \arctan\left(\frac{49}{150000}\right) = 0.019^{\mathrm{o}}$$

then the specified horizontal angular resolution would be 0.019º.

Vertical resolution: The smallest vertical distance or separation between two distinct objects that can be detected in a single scan at a specified distance from the instrument.

The *vertical angular resolution* may be specified in a manner similar to that of the horizontal angular resolution.

***Issues**: The range or depth resolution requires further thought. Instead of horizontal and vertical resolution consider replacing with lateral resolutions.*

Spatial performance*

Spatial performance may be quantified using several different types of measures. The measure that is often used is based on the deviation of corresponding control points. These deviations are frequently combined using the RMS method. Adopting this method, the spatial performance is calculated as follows:

$$\sqrt{\frac{\sum_{i=1}^{n}\left[\left(x_{m,cp\ i} - x_{ref,cp\ i}\right)^2 + \left(y_{m,cp\ i} - y_{ref,cp\ i}\right)^2 + \left(z_{m,cp\ i} - z_{ref,cp\ i}\right)^2\right]^2}{n}}$$

where

$x_{m,cp\,i}, y_{m,cp\,i}, z_{m,cp\,i}$ are the coordinates of control point *i* as measured by the 3D imaging system

$x_{ref,cp\,i}, y_{ref,cp\,i}, z_{ref,cp\,i}$ are the coordinates of control point *i* as measured by an instrument of higher accuracy than the 3D imaging system used

***Issue:** The consensus was that the term is necessary but requires a new definition.*

Additional terms suggested for inclusion to the terminology pre-standard are *beam spot size*, *compensation*, *modular transfer function*, *outliers*, *panoramic imaging*, and *spatial frequency*. Definitions for these terms will be suggested and will be submitted to the standards committee for consideration.

4. RANGING PROTOCOL PRE-STANDARD

Methods that are used to evaluate the performance of 3D imaging systems fall into two general categories: instrument characterization and overall project accuracy. The former category is clear-cut. The latter category addresses questions such as: "How accurate/good is the desired end product, e.g., if quality control were the desired end product, would the generated 3D model be accurate enough to accomplish this task?" and "Did the system perform as intended, e.g., did the information derived from the data reduce the amount of re-work and schedule delays through early detection of construction errors?" Since the overall project accuracy is application dependent, it is not practical to develop evaluation methods for the myriad of possible applications, and further efforts will be required to ascertain common measurements among these applications. If this were accomplished, methods could then be developed to evaluate these measurements. Therefore, instrument characterization was the logical first step.

An instrument characteristic that was ranked highly by the NIST workshop participants in terms of interest and importance was range error. The parameters considered to have the most effect on the range error were target reflectivity, target material, angle of incidence, distance to target, and environmental conditions (temperature and humidity). It was generally agreed that a planar target with known reflectivity should be used. The size of the target would have to be agreed upon.

The 2005 workshop identified issues that need to be considered when developing a ranging protocol. These include:

- The inability of some scanners to acquire a single measurement, i.e., they can only operate in scanning mode. Protocols would then need to be developed for single shot range error and for scanning mode range error, where a planar target would be scanned and a plane fitted through the points. In scanning mode, the point density would then need to be specified.
- The ability of some scanners to average measurements. This can be done by scanning a scene multiple times and averaging the values or by dwelling on a point. Averaging would increase the time to acquire a scan and decrease the noise. Therefore, it was suggested that the scan or measurement time should be reported.
- The determination of the distance intervals for placing the targets. Would the intervals be "constant" or would a more random spacing be required? With regards to the latter, it was felt that knowledge of the physics of the instrument is needed to ascertain potential fail points, e.g., occurrence of mode hopping. The concern then would be that protocols would be non-standard or instrument-specific. For short range evaluations (1 m to 20 m), it was generally felt that the spacing of the targets needs to be smaller than the spacing specified for long range (> 100 m) evaluations.
- The inability to de-couple hardware and software. It was felt that the measurement as processed by the software, provided by either the manufacturer or a third party, should be used and that the software that was used to obtain the measurement should also be reported.
- The ability to center an instrument over a benchmark. It was decided that the manufacturer would have to provide instrument set-up procedures.
- How are the reference measurements obtained, and what is the required uncertainty of these measurements.

A draft ranging protocol was presented at the 2006 workshop. The general concept outlined in the draft protocol was acceptable to the workshop participants with the details to be worked out by the standards committee. The following paragraphs summarize the procedures proposed in the draft and recommended modifications to the draft based on comments from the workshop participants.

The proposed protocol provides a method to evaluate an instrument up to a maximum range of 150 m. There are commercially available instruments with maximum ranges greater than 150 m (the maximum of some instruments are over a kilometer). However, the ranges for most construction applications are within 150 m for the sub-classes of instruments of interest. The sub-classes of these instruments that are of particular interest include those that are ground-based and are capable of capturing information of a scene that is on the order of a large capital project such as process plants, construction sites, buildings, and bridges. Protocols for longer ranges, while deemed important, were not considered at this time for reasons of feasibility and practicality, but may be considered at a later time based on the needs of the 3D imaging community.

An important issue that needed to be considered was whether the ranging protocol should evaluate absolute or relative distance measurements. The vast majority of the workshop participants agreed that only relative distance measurement should be evaluated because the centers of most instruments cannot be easily determined, and thus, the ability to obtain absolute distance measurements would not be possible. It was also decided that ranges at which the instruments should be evaluated should be the minimum (typically 1 m to 2 m) and maximum ranges of the instrument and two other distances. If the maximum range of an instrument is greater than 150 m, then the maximum range evaluated would be 150 m.

In terms of the target, there was consensus that planar targets of varying reflectivity, ≈ 5 %, ≈ 10 %, ≈ 20 %, and ≈ 90 %, should be used. The concentration on lower reflectivities was due to the workshop participants' belief that more significant effects would be observed at lower reflectivities. There was general agreement that the shape of the target could either be square or circular. Also, agreed upon was that three settings for angle of incidence be used, with 0º, 30º, and 60º suggested as possible values.

It was also generally agreed that the reported results should include the measured distance and the measurement error, the amount of time it took to obtain the measurement, the number of points used to obtain that measurement, statistics associated with the measurement (e.g., standard deviation of plane fit), and the filter(s) used, if any (e.g., if the data points were filtered based on return signal strength or range).

There was some discussion relating to the latter two items – fitting algorithms and data filtering. These two items are related to the issue of software and what is considered raw or processed data. The basic function of a 3D imaging system is to convert a returned signal to a range measurement. The conversion is done either within the instrument or the data is sent to the control software where it is converted. How or where that conversion is made is not the issue but that a conversion is made. The resulting data are considered "processed" data and not raw data. The general feeling was that the processed data are what is of interest to the user and what a user will use to generate models, etc. As part of the instrument package, software is generally included for instrument control and data display. Basic geometric fitting algorithms and data filtering based on range, signal quality, intensity, etc. may also be included in this software. If the data are filtered, then the name of the software and filter used should be included in the rated conditions (Form 6.1 in the ranging protocol). However, it was generally agreed that if analysis procedures such as plane fitting algorithms were to be called for in the ranging protocol, they would be algorithms that were based on consensus – either from a commercial package or provided by NIST.

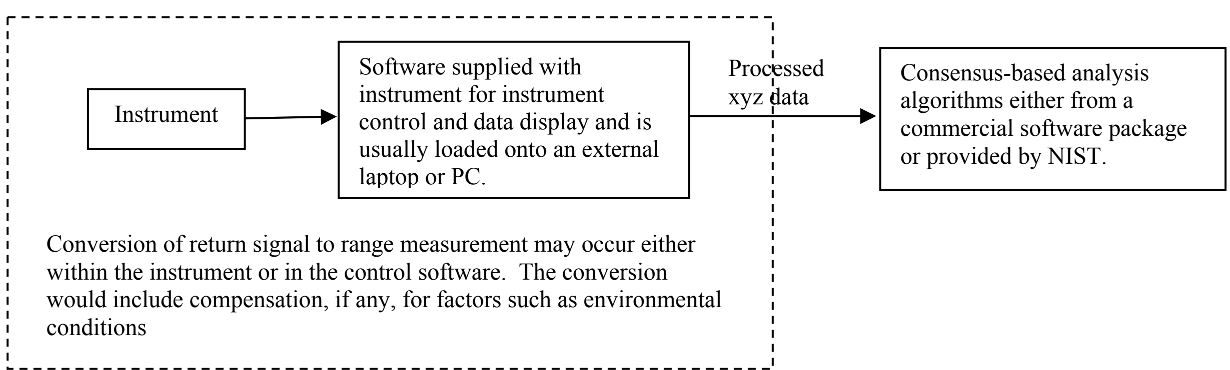


Figure 6. Processed Data.

Some issues raised by the workshop participants concerning the ranging protocol included whether to have separate ranging protocols – one for single point measurements and one for scanning, the ability to align the instrument center with the target center, and the ability to quantify or specify the amount of ambient light[‡] during the evaluations.

SUMMARY

Based on feedback from a series of four workshops held between 2003 and 2006 at NIST, an indoor artifact-based performance evaluation facility was established at NIST. The facility will be used to primarily develop test protocols and performance metrics. Prototype artifacts developed as part of the facility include spheres, a stair artifact, a slotted artifact, large [152 mm (6 in) diameter] SMRs, and planar targets of known reflectivities.

A terminology pre-standard and a ranging protocol pre-standard were developed and presented at the 2006 workshop. The terminology pre-standard consists of common metrology terms such as accuracy and uncertainty and terms that are commonly used in the 3D imaging community. No attempt was made to re-define the common metrology terms, but definitions for the latter set of terms were suggested to provide a common frame of reference. The list of commonly used terminology along with their suggested definitions as well as comments received from the workshop participants were re-produced in this paper.

General consensus existed on the concept of the ranging protocol. There was general agreement that the protocol should evaluate relative distance or displacement and the parameters of interest were target distance, target reflectivity, and target rotation. Some issues that were raised included whether to have separate protocols for single point measurements and for scanning measurements and the ability to align the instrument center with the target center.

The two pre-standard documents will be presented to an ASTM committee as a starting point for developing standards for 3D imaging systems. The activity has been approved by ASTM and is slated to begin in June 2006. Other future efforts include refining and evaluating NIST-developed fitting algorithms for spheres, determining registration uncertainty, and evaluation and testing of the ranging protocol.

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[‡] Solar radiation may be measured with pyranometers. Two approaches may be used to account for solar radiation. The solar radiation measured at the time of the test may be included as part of the "Rated Conditions" or a range of acceptable values may be specified as part of the protocol (i.e., if the measured solar radiation at the time of the test is within specified limits, the test is considered valid).