STANDARD DEFINITIONS OF TERMINOLOGY FOR 3D IMAGING SYSTEMS

PREFACE

In an effort to standardize terminology used for 3D imaging systems, the National Institute of Standards and Technology in conjunction with input from instrument manufacturers and users has developed a common terminology for 3D imaging systems. We are pleased to present this edition of a terminology pre-standard. We expect that the standard terminology document will expand on this pre-standard to include additional common terms and nomenclature.

1.0 Referenced Definitions

The definitions of the terms presented in this section were obtained from various standard documents [1.1, and 1.3] developed by various standards developing organizations. The intent is not to change these universally accepted definitions but to gather, in a single document, terms and their definitions that may be used in current or future standard documents for 3D imaging systems.

In some cases, definitions of the same term from two standards have been presented to provide additional reference. The text between the square brackets to the right of each defined term is the name (as well as, in some cases, the specific section) of the source of the definition associated with that term.

Accuracy of measurement [VIM 3.5]:

Closeness of the agreement between the result of a measurement and a true value of the measurand

NOTES:

1. "Accuracy" is a qualitative concept.
2. The term "precision" should not be used for "accuracy".

Bias (of a measuring instrument) [VIM 3.25]:

Systematic error of the indication of a measuring instrument.

NOTE: The bias of a measuring instrument is normally estimated by averaging the error of indication over an appropriate number of repeated measurements.

Bias [Engineering Statistics Handbook]:

The difference between the average or expected value of a distribution, and the true value. In metrology, the difference between precision and accuracy is that measures of precision are not affected by bias, whereas accuracy measures degrade as bias increases.

Calibration [VIM 6.11]:

A set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards.

NOTES:

1. The result of a calibration permits either the assignment of values of measurands to the indications or the determination of corrections with respect to indications.
2. A calibration may also determine other metrological properties such as the effect of influence quantities.
3. The result of a calibration may be recorded in a document, sometimes called a calibration certificate or a calibration report.

Conventional true value (of a quantity) [VIM 1.20]:

Value attributed to a particular quantity and accepted, sometimes by convention, as having an uncertainty appropriate for a given purpose.

EXAMPLES:

a) At a given location, the value assigned to the quantity realized by a reference standard may be taken as a conventional true value;
b) The CODATA (1986) recommended value for the Avogadro constant, N_A: 6,022 136 7 x 10^{23} mol^{-1}

NOTES:

1. "Conventional true value" is sometimes called assigned value, best estimate of the value, conventional value or reference value. […]
2. Frequently, a number of results of measurements of a quantity is used to establish a conventional true value

Error (of measurement) [VIM 3.10]:

Result of a measurement minus a true value of the measurand.

NOTES:

1. Since a true value cannot be determined, in practice a conventional true value is used (see true value and conventional true value).
2. When it is necessary to distinguish "error" from "relative error", the former is sometimes called "absolute error of measurement". This should not be confused with the "absolute value of error", which is the modulus of error.

Indicating (measuring) instrument [VIM 4.6]

Measuring instrument that displays an indication

EXAMPLES:

a) analog indicating voltmeter;
b) digital frequency meter;
c) micrometer.

NOTES:

1. The display may be analog (continuous or discontinuous) or digital.
2. Values of more than one quantity may be displayed simultaneously.
3. A displaying measuring instrument may also provide a record.

Maximum Permissible Error (MPE) [VIM 5.21]

Extreme values of an error permitted by specification, regulations, etc. for a given measuring instrument.

Measurand [VIM 2.6]:

Particular quantity subject to measurement.

EXAMPLE: vapor pressure of a given sample of water at 20° C.

NOTE: The specification of a measurand may require statements about quantities such as time, temperature and pressure.

Precision [ASTM E456-02]

The closeness of agreement between independent test results obtained under stipulated conditions.

NOTES:

1. Precision depends on random errors and does not relate to the true value or the specified value.
2. The measure of precision is usually expressed in terms of imprecision and computed as a standard deviation of the test results. Less precision is reflected by a larger standard deviation.
3. "Independent test results" means results obtained in a manner not influenced by any previous result on the same or similar test object. Quantitative measures of precision depend critically on the stipulated conditions. Repeatability and reproducibility conditions are particular sets of extreme stipulated conditions.

Precision [Engineering Statistics Handbook]:

1. In metrology, the variability of a measurement process around its average value. Precision is usually distinguished from accuracy, the variability of a measurement process around the true value. Precision, in turn, can be decomposed further into short term variation or repeatability, and long term variation, or reproducibility.

2. A fuzzy concept term for the general notion that one knows more or has shorter confidence intervals if one has more data; that is, more data gives greater precision in answers and decisions.

Random Error [VIM 3.13]:

Result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions:

NOTES:

1. Random error is equal to error minus systematic error.
2. Because only a finite number of measurements can be made, it is possible to determine only an estimate of random error.

Relative Error [VIM 3.12]:

Error of measurement divided by a true value of the measurand.

NOTE: Since a true value cannot be determined, it practice a conventional true value is used.

Repeatability (of results of measurements) [VIM 3.6]:

Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement.

NOTES:

1. These conditions are called repeatability conditions.
2. Repeatability conditions include:
   - the same measurement procedure
   - the same observer
   - the same measuring instrument, used under the same conditions
   - the same location
   - repetition over a short period of time
3. Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results.

Reproducibility (of results of measurements) [VIM 3.7]:

Closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement.

NOTES:

1. A value statement of reproducibility requires specification of the conditions changed.
2. The changed conditions may include:
   - principle of measurement
   - method of measurement
   - observer
   - measuring instrument
   - reference standard
   - location
   - conditions of use
   - time.
3. Reproducibility may be expressed quantitatively in terms of the dispersion characteristics of the results.
4. Results are here usually understood to be corrected results.

Systematic Error [VIM 3.14]:

Mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus a true value of the measurand.

NOTES:

1. Systematic error is equal to error minus random error.
2. Like true value, systematic error and its causes cannot be completely known.
3. For a measuring instrument, see “bias”.

Uncertainty of measurement [VIM 3.9]:

Parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

NOTES:

1. The parameter may be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.
2. Uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results of series of measurements and can be characterized by experimental standard deviations. The other components, which can also be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information.
3. It is understood that the result of the measurement is the best estimate of the value of the measurand, and that all components of uncertainty, including those arising from systematic effects, such as components associated with corrections and reference standards, contribute to the dispersion.

True value (of a quantity) [VIM 1.19]:

Value consistent with the definition of a given particular quantity

NOTES:

1. This is a value that would be obtained by a perfect measurement.
2. True values are by nature indeterminate.
3. The indefinite article “a”, rather than the definite article “the”, is used in conjunction with “true value” because there may be many values consistent with the definition of a given particular quantity.

<u>REFERENCES</u>

1.1 ASTM International, ASTM E456-02, “Standard Terminology Relating to Quality and Statistics,” American Society of Testing and Materials.

1.2. Engineering Statistics Handbook, http://www.itl.nist.gov/div898/handbook/glossary.htm

1.3. International Organization for Standardization, International Vocabulary *of Basic and General Terms in Metrology*, 1993. (VIM)

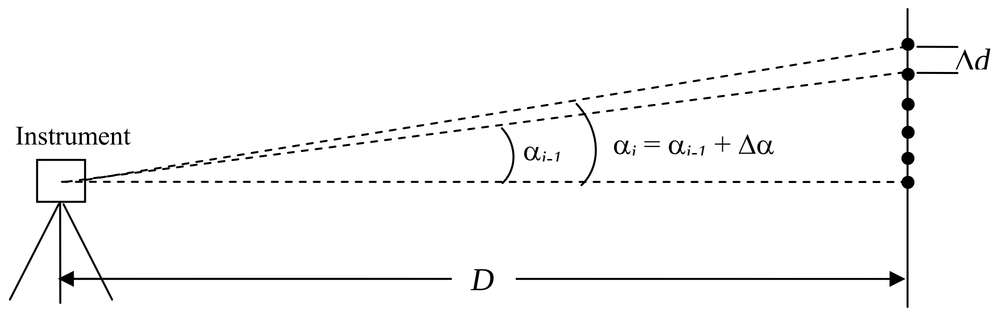
2.0 Standard Definitions for 3D Imaging Systems

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. These systems include 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 directions. The angular increment may also be known as the angle step size.



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

The angular increment, specified by the instrument manufacturer, is typically a minimum value, and the achievable point density may be inferred from this value. A smaller angular increment results in a denser point cloud. The angular increment can be used to determine the distance, $\Delta\, d$, between contiguous pixels or points 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

Visible or recoverable reference points common to both an independent source of 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 sometimes referred to as fiduciaries.

Control points may be used to:

- register two or more point clouds
- infer the accuracy of the derived output from 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 of higher accuracy than the 3D imaging system used. The distances (reference distances) between any two of these control points can be calculated using the reference locations. Similarly, the distances (measured distances) between corresponding control points 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) and an FPA detector, such that the range image is acquired simultaneously in one burst. This allows for the achievement of 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 FOV of the instrument.

Frame Rate

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 is generally a metric that is mainly applicable to real-time systems such as flash LADARs, since most commercial scanning LADARs 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 as 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 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).

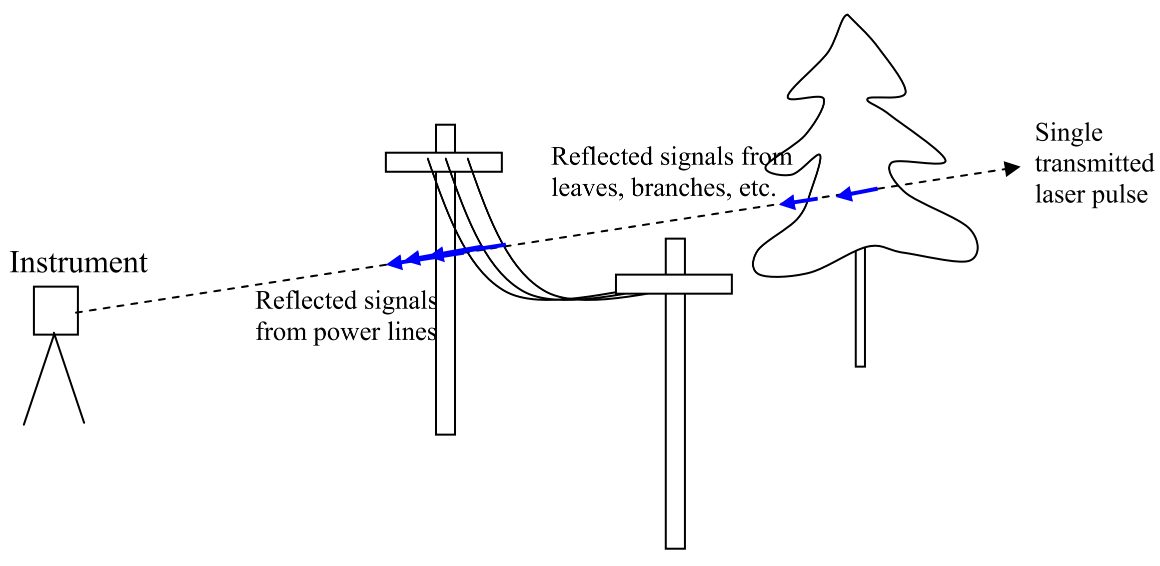
Mixed Pixels

Mixed pixels or phantom points are a result of the way most instruments process multiple returns. When a laser beam hits the edge of an object, the beam is split. Part of the beam is reflected by the object and the other part is reflected by another object beyond. Thus, the reflected signal contains multiple returns. Typically, the reported range measurements in such cases are the averages of the multiple returns which often fall between the two objects; hence, recording points that do not exist and are referred to as mixed pixels or phantom points.

The number of mixed pixels may be reduced by having a smaller initial beam spot size, smaller beam divergence, and the capability of the 3D imaging system to record multiple returns.

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.



Phantom Points

See "mixed pixels."

Point Cloud

A collection of 3D points, frequently in the hundreds of thousands, as obtained using a 3D imaging system.

Point Density

The number of points per unit area.

EXAMPLE:

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

$$x = 2 \times r \tan\left(\frac{\theta}{2}\right)$$

$$y = 2 \times r \tan\left(\frac{\varphi}{2}\right)$$

a = nominal number of points in row

$= \dfrac{\theta}{\Delta\theta} + 1$

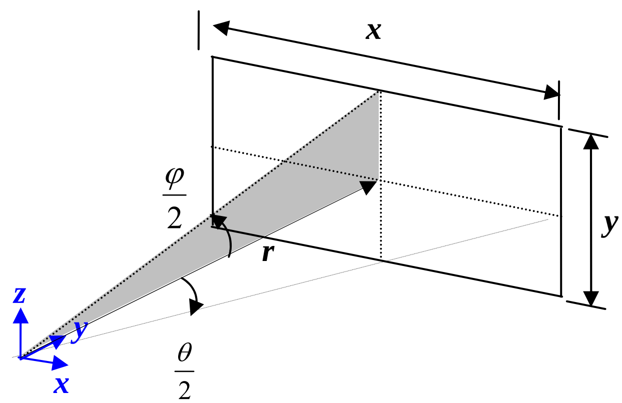
b = nominal number of points in a column

$= \dfrac{\varphi}{\Delta\varphi} + 1$

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



Registration

Registration is required when two or more sets of coordinate data are obtained with each data set having its own frame of reference or local reference frame. The task of 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 to a global reference frame.

Registration Error

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

Global: 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.

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

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

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

Example, given the following information,

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

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

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

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.

In a similar manner to the horizontal angular resolution, the *vertical angular resolution* may be specified.

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

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

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

3.0 Standard Acronyms for 3D Imaging Systems

APD

An acronym for “Avalanche Photo Diode”.

CCD

An acronym for “Charge Coupled Device”. An imaging sensor where individual pixels in an array are allowed to transport, store, and accumulate optically-generated charge carriers to defined sites within the device. CCD principles, combined with on-chip timers for each pixel can be used to create a time-of-flight focal plane array.

FOV

An acronym for “Field-of-View”. The angular coverage of a scene and the units normally associated with FOV are degrees, e.g., The LADAR has an FOV of 300° (horizontal) x 80° (vertical).

FPA

An acronym for “Focal Plane Array”. A 2D “chip” in which individually addressable photo sensitive “pixels” can be accessed.

LADAR

An acronym for a laser (light) detection and ranging (LADAR) system. A LADAR is a system that is used to obtain multiple distance measurements of a scene. These measurements, several thousand to several million, are commonly referred to as a “point cloud”. The distances are measured by measuring the time-of-flight of a laser pulse, the phase difference of a laser pulse, or by triangulation.

The term LIDAR has been commonly associated with airborne laser radars while the term LADAR has been commonly associated with ground-based laser radars.

LIDAR

An acronym for a light detection and ranging (LIDAR) system. Similar to the term LADAR, a LIDAR system is used to obtain multiple measurements (e.g., distances, velocities, chemical concentrations) of a scene.

The term LIDAR has been commonly associated with airborne laser radars and those systems that perform remote sensing of the atmosphere.