



MEASUREMENT TECHNOLOGIES IN  
QUALITY CONTROL PURPOSES –  
TEACHING MANUAL

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## INTRODUCTION

Quality control is a common process used in the manufacturing of parts. Although this concept was made popular during the industrial revolution, it has existed for thousands of years. Indeed, historians made references to quality control as far back as 3000 B.C. in Babylonia, from the code of Hammurabi, in which laws reflected a concern for quality in antiquity. The quality control process originated from Egypt, where a system for quarrying and dressing stone was designed for building pyramids. Centuries later, Greek architecture outperformed Egyptians; moreover, shipbuilding operations in Venice showed the very early stages of production control and standardization.

Quality control took a giant step with the Industrial Revolution, which completely revisited the factory system. The factory system, with its emphasis on product inspection, started in Great Britain in the middle of 1750s and grew during the Industrial Revolution in the early 1800s. The concept of the interchangeability of parts was introduced with the manufacturing of 15 000 muskets for the US Federal Government by Eli Whitney, which involved, for the first time, inspections conducted by individuals—and not directly part of the production process. In 1911, the publication of Frederick Winslow Taylor's book *Principles of Scientific Management* propelled the specialization of labor and quality assurance. Among his contributions, Taylor brought the notion of process analysis and quality control by inspecting final products. A few years later, in the mid-1920s, statistical quality control (SQC) emerged from the Western Electric plant of the Bell System. This principle was the forerunner of today's total quality management (TQM).

Walter Shewhart, a Bell Laboratories physicist, designed the original version of SQC to achieve zero defects during the mass production of complex telephone exchanges and telephone sets. In 1931, Shewhart published his landmark book: *Economic Control of Quality of Manufactured Product*. This book provided a precise and measurable definition of quality control and purported statistical techniques for evaluating production and improving quality. During World War II, W. Edward Deming and Joseph Juran, both former members of Shewhart's group, separately developed the versions that are used today.



Today, it is generally accepted that the Japanese owe their product leadership in part to adopting the precepts of Deming and Juran. According to Peter Drucker, the U.S. ignored the contributions of Deming and Juran for 40 years; the US is now only beginning to convert to SQC.<sup>1</sup>

The following figure summarizes the main contributors and events that marked the improvement of the concept of quality.

1900	<ul style="list-style-type: none"> <li>• FW Taylor: Product inspection in quality</li> <li>• Redford: Quality in product design</li> </ul>
1924	<ul style="list-style-type: none"> <li>• Walter Shewhart: Statistical Process Control (SPC) / Control charts</li> </ul>
1930's	<ul style="list-style-type: none"> <li>• Dodge &amp; Romig: Acceptance sampling tables</li> </ul>
1940's	<ul style="list-style-type: none"> <li>• Deming: Statistical quality control (SQC) in Japan</li> </ul>
1950's	<ul style="list-style-type: none"> <li>• Quality assurance in America</li> <li>• Juran: "Cost of quality"</li> </ul>
1960	<ul style="list-style-type: none"> <li>• Philip Crosby: Zero defect</li> </ul>
1970's	<ul style="list-style-type: none"> <li>• Preventing defects than correcting them</li> </ul>
1980's	<ul style="list-style-type: none"> <li>• TMQ / British Standards (BS)</li> </ul>
2000...	<ul style="list-style-type: none"> <li>• Quality shift from manufacturing to service</li> <li>• "Business excellence"</li> </ul>

Source: <http://www.rajeshthimane.com/56/academics/history-of-quality-control.html>

Figure 1: Main contributors in the improvement of the concept of quality.

Geometric Dimensioning and Tolerancing (GDT) symbols have been used since at least the turn of the century. GDT was especially important during the Second World War due to the extremely high-volume production of Liberty ships, aircraft, and ground vehicles. The automotive industry, with its high volumes, has also benefited from GDT. The computer industry, in particular mass storage manufacturers, has used GDT extensively to increase yields of high-volume and low-margin hard disk drives. However, as with most engineering and scientific methodologies, GDT was not rigorously established and documented until later in the twentieth century. The American

<sup>1</sup> URL: <http://totalqualitymanagement.wordpress.com/2009/08/25/a-brief-history-of-quality-control/>

National Standards Institute publication in 1982 of ANSI Y14.5M-1982 was a turning point in the rigorous, unambiguous standardization of the methodology.<sup>2</sup>

This teaching manual is divided into three main sections. The first part gives an overview of the theory, techniques, and concepts used in Quality Control (QC) applications, including the various measuring technologies used. The second part provides deeper insight into the theory and principles used at each stage of the typical quality-control workflow. Moreover, the third part is a lab guide that provides the different steps to perform dimensional inspection using Creaform's HandyPROBE.

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<sup>2</sup> URL: <https://www.efunda.com/designstandards/gdt/introduction.cfm>

## 1. QUALITY CONTROL: THE THEORY

### 1.1.WHAT IS QUALITY CONTROL?

There are several definitions and types of definitions of quality depending on the application. Manufacturing-based definitions associate quality with the conformance of a product to its specifications. Quality control (QC) is a process that aims to review the quality of all factors involved in the production process.<sup>3</sup>

### 1.2.WHO USES QUALITY CONTROL?

Nearly every industry, at various levels, is required to use QC. Regardless of the type of industry or activity, each company needs to evaluate its production quality to improve its production, remain competitive, and sustain a sound reputation. QC is not only about eliminating the defective parts (objects) but also ensuring a comprehensive evaluation of the commercialized product's quality.

### 1.3.WHY QUALITY CONTROL?

Using QC enables a company to improve its manufacturing processes. Therefore, QC has several benefits for a company, which can be divided as follows:

#### *INTERNAL BENEFITS*

- ▶Reduce costs
- ▶Increase profitability
- ▶Decrease reject rates/costs
- ▶Increase customer retention

#### *EXTERNAL BENEFITS*

- ▶Increase customer satisfaction
- ▶Ensure product specifications
- ▶Increase products average quality
- ▶Appropriate intangibles

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<sup>3</sup> URL: [http://en.wikipedia.org/wiki/Quality\\_control](http://en.wikipedia.org/wiki/Quality_control)

## 1.4.METROLOGY

Metrology is the science of measurement. Metrology is defined by the International Bureau of Weight and Measures (BIPM) as “the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology.”<sup>4</sup>

### 1.4.1. KEY ORGANIZATIONS

The International System of Units (SI), successor of the metric system, was officially founded in 1960 following a resolution made in the 11th *Conférence Générale des Poids et Mesures* (CGPM). All units of measurement can be reduced to a small number of fundamental standards with this system, which dedicates the necessary care to continuously improve their definitions.

Although universal, the implementation of the metre unit, defined as a proportion of the quarter meridian, was clearly difficult to implement. This explains why its standard was first stored in the archives as the international prototype metre in 1889.<sup>5</sup>

The Convention of the Metre (Convention du Mètre) is a treaty that created the International Bureau of Weights and Measures (BIPM), an intergovernmental organization under the authority of the General Conference on Weights and Measures (CGPM) and with the supervision of the International Committee for Weights and Measures (CIPM). The BIPM acts in matters of world metrology, particularly concerning the demand for measurement standards of ever-increasing accuracy, range, and diversity. It also helps to address the need to demonstrate the equivalents between national measurement standards.<sup>6</sup>

International metrology is established through the coordination of activities between the NMIs of individual countries. The roles of NMIs are: ensuring primary national standards, offering a calibration service to accredited laboratories and companies, and increasingly

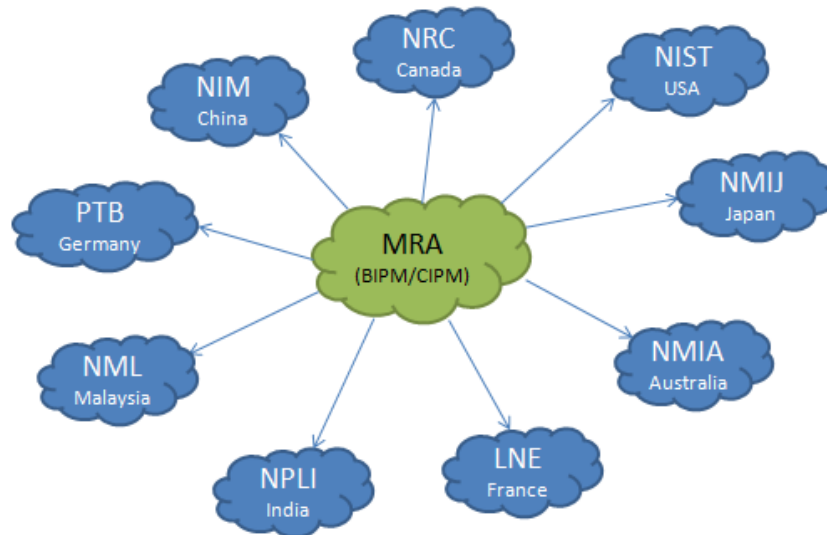
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<sup>4</sup> URL: <http://www.bipm.org/en/convention/wmd/2004/>

<sup>5</sup> URL: <http://www.french-metrology.com/en/history/history-mesurement.asp>

<sup>6</sup> URL: <http://www.bipm.org/en/convention/>

playing a role of transferring knowledge to countries. Some of the well-known NMIs are: LNE (France), NIST (United States), PTB (Germany), and NIM (China).



Source: Creaform Metrology Services

Figure 2: NMIs of different countries.

#### 1.4.2. VOCABULARY

Confusion can occur with metrology technical vocabulary. The following definitions are reminders of several fundamental notions.

##### 1.4.2.1. PRECISION, TRUENESS, AND ACCURACY

In metrology, **precision** refers to the dispersion of measurements. The measurement error (the mean) can be close to zero even if the system is very not precise (it nevertheless must have a good trueness). In other words, the less the measurement data is scattered, the more equipment is precise. A formal definition of precision is: closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects and under specified conditions.

The word **trueness** gives information on the difference between the mean of measurements and the real dimension, regardless of dispersion. In other words, the more the mean of measurements is close to the nominal value, the more the equipment has good trueness. A formal definition of trueness is: closeness of agreement between the average of an infinite number of replicate measured quantity values and reference quantity value.

**Accuracy** is the conformity between scan data and reality. To evaluate the accuracy of a measuring device, such as a laser scanner, the data acquired with the device should be compared to the data acquired with a more accurate measurement tool (e.g.: a coordinate measuring machine (CMM)). In addition, the measured item must be normalized.

A more formal definition of measurement accuracy is: the closeness of agreement between a measured quantity value and a true quantity value.<sup>7</sup> As illustrated in the following figure, the accuracy of a system is a combination of its precision and trueness.

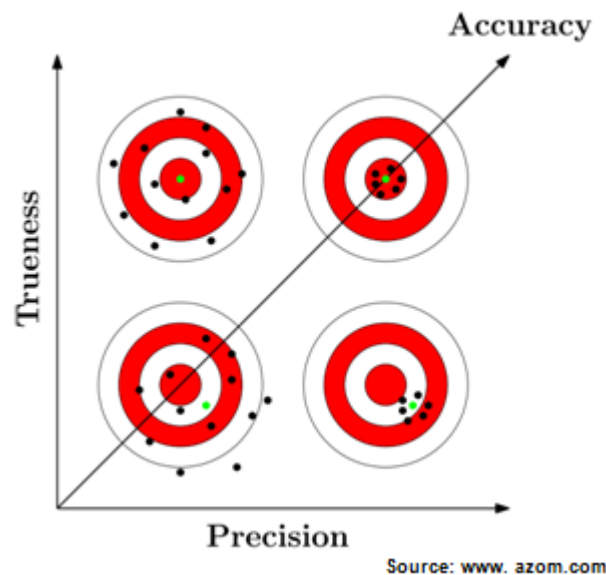


Figure 3: Representation of accuracy, trueness, and precision.

#### 1.4.2.2. REPEATABILITY

<sup>7</sup> URL: [http://www.iasonline.org/Calibration\\_Laboratories/definitions.pdf](http://www.iasonline.org/Calibration_Laboratories/definitions.pdf)

**Repeatability** is the capacity to reproduce a same action or result in similar conditions. This represents precision under a set of identical conditions of measurement:

- ▶ Same operators
- ▶ Same measuring system
- ▶ Same measurement procedure
- ▶ Same operating conditions
- ▶ Same site
- ▶ Same or similar objects
- ▶ Short time period

#### 1.4.2.3. *REPRODUCIBILITY*

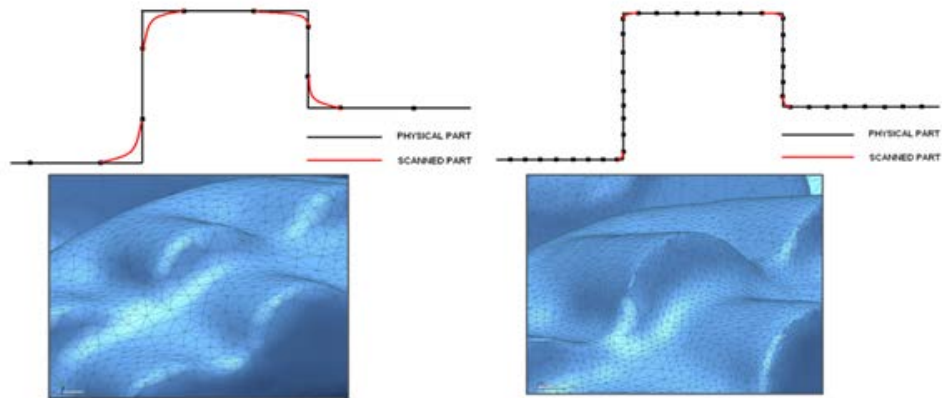
**Reproducibility** is the ability of measurements/testing to be reproduced by different people in different conditions. This represents the precision under a set of variable conditions of measurement:

- ▶ Different operators
- ▶ Different measuring system
- ▶ May use different measurement procedure
- ▶ Same or similar objects

#### 1.4.2.4. *RESOLUTION*

The **resolution** of a sensor is the smallest change in a measurement that causes a perceptible change in the corresponding indication. In terms of scanning, resolution refers to the level of detail that the sensor can acquire.

Note: **Accuracy** and **resolution** are **two different factors**. They are closely linked when the level of detail is higher than the output resolution. The figure below demonstrates the impact of resolution on the accuracy for a part (object) with sharp features.

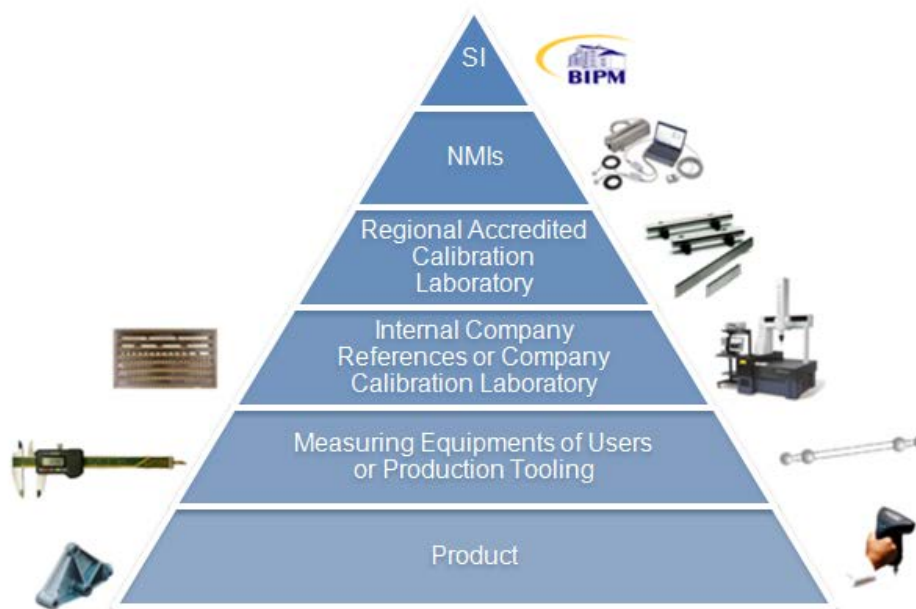


Source: Creaform Metrology Services

Figure 4: Representation of the difference between accuracy and resolution.

### 1.4.3. STANDARDS AND TRACEABILITY

The National Institute of Standards and Technology (NIST) defines traceability as an “establishment of an unbroken chain of comparisons to stated references each with a stated uncertainty.”<sup>8</sup>



Source : Creaform Metrology Services

Figure 5: Representation of the traceability chain.

<sup>8</sup> URL: [http://www.nist.gov/pml/mercury\\_traceability.cfm](http://www.nist.gov/pml/mercury_traceability.cfm)



#### 1.4.4. MEASUREMENT UNCERTAINTY

**Uncertainty** is described as the doubt about the validity of a measurement result. A measurement never gives the true value; however, it is the best estimation of it. This way, a measurement is only complete if it is accompanied by a statement of the associated uncertainty. The following figure shows the main sources of uncertainty.

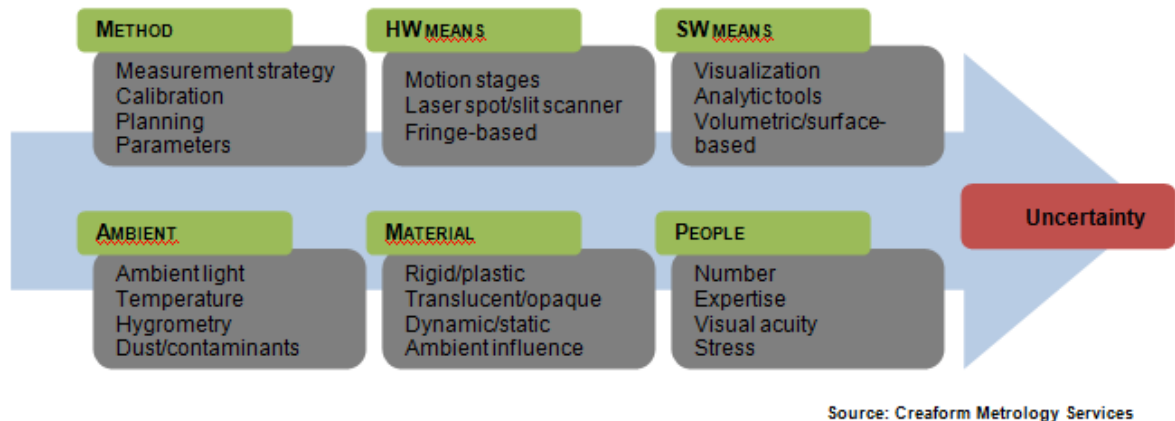


Figure 6: Representation of main sources of uncertainty.

Equipment performance is not the only thing to consider for best accuracy. Due to several potential sources of error, uncertainty is difficult to determine. It is a decisive factor when it is required to make an informed inspection decision.

#### 1.4.5. GEOMETRIC DIMENSIONING AND TOLERANCING (GD&T)

##### 1.4.5.1. DEFINITION: WHAT IS GD&T?

GD&T is the system for defining and communicating engineering tolerances. It uses a symbolic language on engineering drawings and computer-generated, three-dimensional solid models that explicitly describe nominal geometry and its allowable variations. GD&T gives an indication to the manufacturing staff and machines what degree of accuracy and precision is required on each controlled feature of the object. GD&T is used to define: the nominal (theoretically perfect) geometry of parts (objects) and assemblies, the allowable variation in form and possible size of individual features,

and the allowable variation between features.<sup>9</sup> In other words, GD&T uses a language for mechanical engineering drawings that includes a set of symbols, rules, definitions, and conventions that aims to efficiently and accurately communicate the geometry requirements for features on components and assemblies.

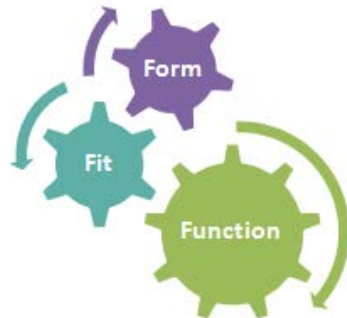
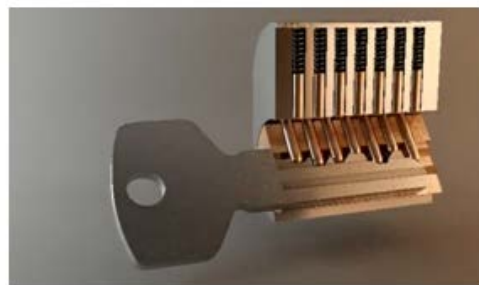
#### 1.4.5.2. FORM, FIT, AND FUNCTION

When applied to objects that are part of an assembly, GD&T is often used to make sure that the different components fit together. This principle is based on the **Form – Fit – Function** idea.

An object has different dimensional characteristics, such as its shape, size, or dimensions. The key below (Figure 6) is composed of a head and tooth-shaped stem. It also features a corresponding lock with a chamber and key barrels (**Form**).

It will be unlocked only if the key's teeth push the barrels into the right position. The key and lock need to have compatible dimensions to interact: the thickness, length, and shape of the teeth are crucial parameters to create the assembly key-lock (**Fit**).

When the key and the lock fit together, the right barrels are raised and the lock can be opened. The action the key is designed to produce is then performed (**Function**).



Source: Creaform Metrology Services

Figure 7: Representation of the Form – Fit – Function concept.

<sup>9</sup> URL: [http://en.wikipedia.org/wiki/Geometric\\_Tolerancing](http://en.wikipedia.org/wiki/Geometric_Tolerancing)

In sum, the dimensional control of objects guarantees that the **forms** will **fit** well together and create the **function** that the product is designed for.

#### 1.4.5.3. *WHY GD&T?*

The growing sophistication and complexity in advanced design, engineering, and manufacturing requires a dimensional control on manufacturing objects to ensure successful end products. Therefore, effective and accurate communication regarding geometric requirements is of the utmost importance. GD&T includes an international language that meets ISO standards and is used in mechanical engineering drawings to accurately communicate geometry requirements regarding the features of a part. GD&T is now part of most QC applications in which specific geometric elements on a part must respect given tolerances.

GD&T is generally used to control geometric dimensions that cannot be measured directly, such as the cylindricity of a cylinder, parallelism between two planes, surface profile, etc. Therefore, GD&T tolerances usually involve computations with measurements to obtain the desired measured zones (specified by the type of tolerance). Most metrology software now includes very efficient tools to perform these computations—all while meeting ISO standards.

#### 1.4.5.4. *VOCABULARY*

GD&T and dimensional control in general are described using a very specific vocabulary. The following are a few definitions of these fundamental notions.

**Nominal value:** Perfect value that the part is supposed to reach according to the drawings or the 3D conception model.

**Actual value:** Real value of the part (physically).

**Measured value:** Value acquired with the measuring system.

**Tolerance:** Allowance for a specific variation in the size and geometry of a part or range of acceptable values. A tolerance is defined either by a plus/minus interval around the nominal value or by specifying the limit values. A tolerance can also be unilateral or bi-lateral.

**Deviation:** Deviation is the difference between the measured value and the nominal value. It indicates if the measured dimension is in or out the tolerance range—and if it is accepted or not.

**Feature control frame:** A feature control frame is a rectangular box that is divided into compartments within which the geometric characteristic symbol, tolerance value, modifiers, and datum references are placed.

#### 1.4.5.5. TOLERANCES

An actual part dimension never exactly fits the nominal value. Moreover, with the measurement uncertainty, it is even truer for a measured dimension.

Part dimensions have a functional range, which means that for a certain range of values, the functioning or quality of the part will not be affected. Tolerances are the permissible limits of variation in dimensions. They are usually specified to allow imperfections on the part without compromising quality and performance.

Geometrical tolerances are often expressed in the form of a plus/minus interval, such as following: **1mm +/- 0.1mm** or **0.5mm +0.1mm/-0.2m**. They are adapted to each part, depending on the type of industry, material, and level of accuracy needed for the part. Tolerances are specified in 2D drawings or 3D models for each dimension.

The analysis of the measured value, in relation to the tolerance range, leads to the validation or rejection of the conformity for the specific dimension.

#### 1.4.5.6. TOLERANCE ZONES

Depending on the element that needs to be controlled on a part, it can involve different type of tolerance zones. Indeed, GD&T usually implies tolerances that are applied directly on the features of a part, rather than just on one size dimension. Form tolerances, such as cylindricity, sphericity, straightness, and circularity are good examples. In the case of cylindricity applied to a cylinder, the tolerance zone would consist of two concentric cylinders of which the difference in diameters equals the value specified by the tolerance (Figure 8).

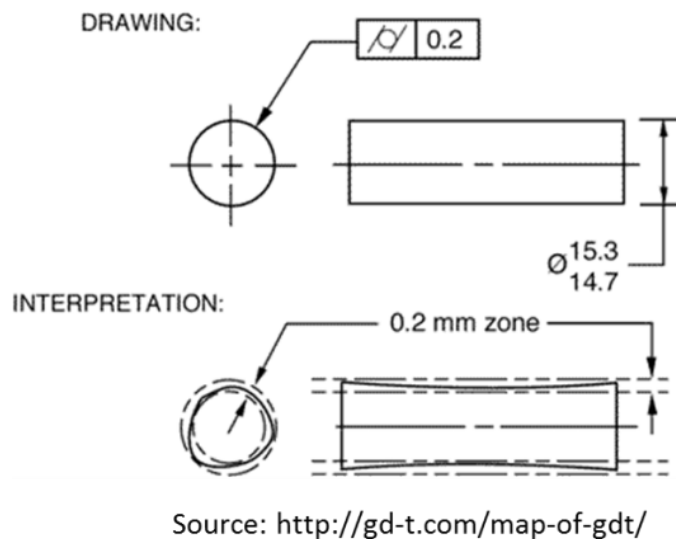


Figure 8: Representation of tolerance zone of a cylindricity tolerance.

Depending on the combination of the controlled feature and datum feature, the tolerance shape can vary. For instance, the perpendicularity between two planes leads to a linear tolerance zone. In this case, the tolerance zone is defined as an envelope within two parallel planes that is spaced using the distance specified by the tolerance and perfectly perpendicular to the datum(s) reference. The perpendicularity between an axis and a plane leads to a cylindrical tolerance zone. The cylinder has the diameter specified by the tolerance and is perfectly perpendicular to the plane.

In all cases, the measured zones must fit within the tolerance zones specified by the tolerance type to meet requirements.

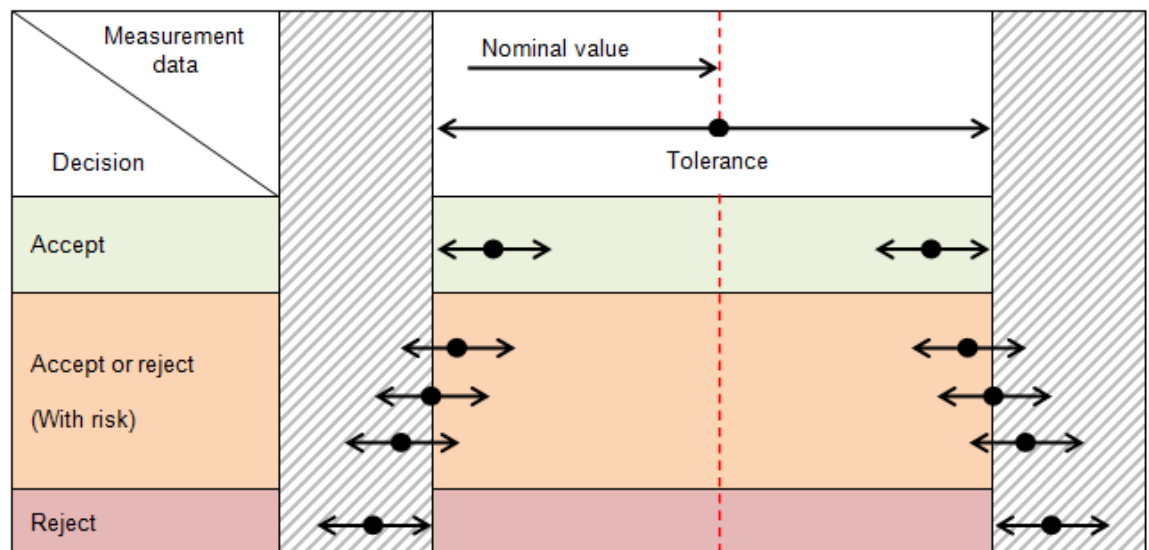
#### 1.4.5.7. VALIDATION OF THE CONFORMITY OF A DIMENSION

For many purposes, measured results have to confirm or reject the conformity of a part's dimension. Basically, a measurement inside the tolerance is valid, whereas a measurement outside the tolerance is invalid.

<i>TOLERANCE</i>	<i>MEASUREMENT</i>	<i>RESULT</i>
1mm +/- 0.1mm	1.35 mm	Invalid
1mm +/- 0.1mm	1.05 mm	Valid

Table 1: Validation of measured results.

The uncertainty of the measurement device has a strong influence on the validation of a dimension. The figure below shows the three possible situations for a measured dimension.



Source: Creaform Metrology Services

Figure 9: Representation of decisions in validation of measurement.

#### 1.4.5.8. DATUM AND DATUM FEATURES

Tolerance and data validation can also be expressed in comparison with a reference entity called datum. A datum is a virtual ideal plane, line, point, or axis that is established from the physical features of a real part that has an important functional relation with the function of the entity being controlled. These physical features are called datum features. Datum features are generally identified on 2D drawings by a capital letter and a datum feature triangle (Figure 10) and are referred to within feature control frames. A datum can be considered as the perfect geometric counterpart of a datum feature. In the case of a physical hole on a part, the datum would be the largest pin or shaft (free of form defects) that can be inserted in this hole. In the case of a flat surface on a part, the corresponding datum would be the perfectly flat surface on which the flat surface of the part is in contact with.

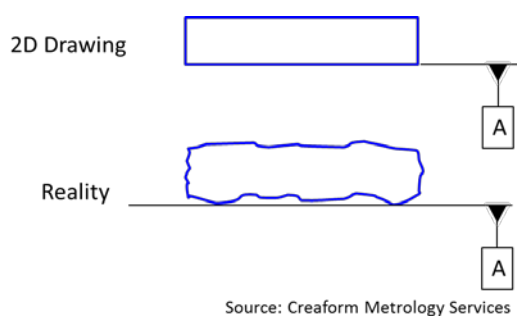
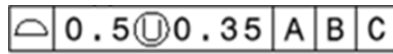


Figure 10: Datum vs datum feature.

In practice, granite tables are often used to simulate datums; they are rigid and usually have a low flatness. The main purpose of using datums, instead of datum features, is to improve the repeatability of inspections since the features on a manufactured part are never perfect. Indeed, performing data validation using datum features (real features of the part) as references lead to poor repeatability. The reason: the results are strongly affected by the location where the points have been recorded on the part.

It is important to mention that using datums results in a specific alignment between the data and the reference object, which is usually a 3D CAD model to allow for comparisons. Indeed, up to three datums can be used at a time. In the case in which three datums are used, they are called (from left to right) primary, secondary, and tertiary datums.

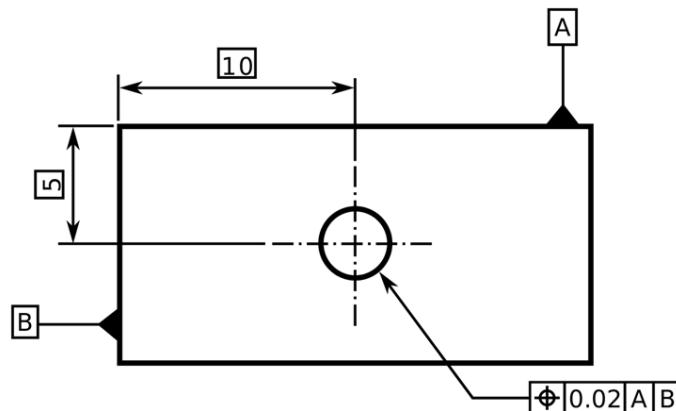


Source: Creaform Metrology Services

Figure 11: Example of a feature control frame using three datums.

Six degrees of freedom (three rotations and three translations) must be constrained to perform an alignment between the data and reference object. The primary datum is the more influent on the alignment, because it constrains more degrees of freedom. The remaining degrees of freedom are blocked by the other datums, where the secondary datum is also more influent than the tertiary datum. Depending on the nature of the primary datum, it does not block the same degrees of freedom. For instance, a plane constrains a total of three dots, which are two rotations and one translation. If the primary datum is an axis, it constrains four degrees of freedom (two rotations and two translations). In the case of a primary datum point, it only locks three translations. If less than 3 datums are used, the reference is under-constrained and can be considered to be less restrictive. That usually means that the metrology software can use the residual mobility to find the alignment that minimizes the deviations.

#### 1.4.5.9. CATEGORIES OF TOLERANCES AND SYMBOLS

















Source: [http://en.wikipedia.org/wiki/Geometric\\_dimensioning\\_and\\_tolerancing](http://en.wikipedia.org/wiki/Geometric_dimensioning_and_tolerancing)

Figure 12: Example of a typical GD&T callout.

As shown in Figure 12, GD&T tolerances are generally provided in a feature control frame on a 2D drawing with an arrow indicating on which feature it applies. The datum(s) used by a GD&T tolerance should always be defined on the same drawing. As



described earlier, the main purpose of geometric dimensioning and tolerancing is to efficiently and accurately communicate geometry requirements for associated features on components and assemblies. The different geometry requirements can be expressed in five main tolerance categories: form, profile, orientation, location, and run-out tolerances. Each one of these categories involves different tolerances that aim to control specific geometrical elements on a part. The following table summarizes the types of GD&T tolerances along with their associated symbols and short descriptions.

	GEOMETRICAL FEATURES	SYMBOL	DESCRIPTION
FORM	Straightness		The condition in which an axis is a straight line (or, in the case of a centerplane, each line element is a straight line).
	Flatness		The condition of a surface having all of its elements in one plane.
	Circularity		The condition in which all points of a surface of revolution, at any section perpendicular to a common axis, are equidistant from that axis.
	Cylindricity		The condition of a surface of revolution in which all points of the surface are equidistant from a common axis.
PROFILE	Profile of a line		A geometric tolerance that limits the amount of errors for line elements relative to their true profile.
	Profile of a surface		A geometric tolerance that limits the amount of errors a surface can have relative to its true profile.
ORIENTATION	Perpendicularity		The condition that results when a surface, axis, or center plane is exactly 90° to a datum.
	Angularity		The condition of a surface, centerplane, or axis being exactly at a specified angle.
	Parallelism		The condition that results when a surface, axis, or centerplane is exactly parallel to a datum.
LOCATION	Symmetry		The condition in which the median points of all opposed elements of two or more feature surfaces are congruent with the axis or centerplane of a datum feature.
	Positional tolerance		The zone within which the axis or centerplane of a feature is permitted to vary from a true (theoretically exact) position.
	Concentricity		The condition in which the median points of all diametrically opposed elements of a cylinder (or a surface of revolution) are congruent with the axis of a datum feature.
RUNOUT	Circular runout		A composite control that affects the form, orientation, and location of the circular elements of a part feature relative to a datum axis.
	Total runout		A composite control affecting the form, orientation, and location of all surface elements of a diameter (or surface) relative to a datum axis.

Source: [http://www.etinews.com/gdt\\_symbols.html](http://www.etinews.com/gdt_symbols.html)

Table 2: Categories of tolerances and symbols.

Form tolerances apply to individual features; this means that no datums are needed. Regarding profile tolerances and depending on the situation, they can apply to individual or related features. For other tolerances, namely the orientation, location, and run-out tolerances, they apply to related features and datums that are required.

#### 1.4.5.10. TOLERANCE MODIFIERS

GD&T tolerances can also include modifiers within the feature control frame that often have an impact on the size of the tolerance zone or the resulting measured values. The following table summarizes the most common modifiers that are found inside feature control frames.







SYMBOLS	MODIFIER NAME	DESCRIPTION
	Maximum Material Condition (MMC)	The condition in which a feature of size includes the maximum amount of material everywhere within the stated limits of size.
	Least Material Condition (LMC)	The condition in which a feature of size includes the least amount of material everywhere within the stated limits of size.
	Projected Tolerance Zone	A tolerance zone that is projected above the part surface.
	Free State Variations	Dimensions and tolerances apply in a free state condition.
	Tangent Plane	The tolerance applies to a plane established by the high points of the surface.
	Unilateral and Unequally Disposed Profile	Unequal tolerance zone with respect to the nominal value, specifying the upper limit.

Table 3: Most common GD&T tolerance modifiers.

### 1.5.MOST COMMON MEASURING TECHNOLOGIES USED FOR QC

Recent innovations about the development of more advanced inspection devices have revolutionized the industry as the inspection process has become extremely more accurate and efficient. Therefore, QC in manufacturing is used, more than ever, in a very wide range of applications that involve inspections on a wide range of part types and sizes. Moreover,

environment conditions in which the part is inspected vary a lot; this leads to completely different approaches to inspection techniques. Indeed, depending on the part to be inspected and requirements, inspection techniques and measuring instruments can vary a lot.

Recent advancements have advanced QC even further by allowing the inspection of new features that could not be measured before, such as the computation of complex GD&T. It is important to mention that measurement devices of new technologies are useful to perform measurements with a high accuracy; furthermore, they can also measure things that cannot be measured with simple measuring tools, such as a tape or a caliper (i.e., distances between points having obstacles in between, angles between axes or planes, surface profiles, etc.). Another good example of something that is hard to measure without a new device is trying to find the center of a hole on a plate.

The most common measuring technologies used in the industry for QC purposes are grouped into two main categories: contact and non-contact technologies. Both solutions have advantages and weaknesses and used depending on the application. Moreover, the principles of optical 3D measuring and photogrammetry are detailed in this section as they leverage useful technologies that are part of the operating principles of many 3D scanning and probing solutions.

#### *1.5.1. OPTICAL 3D MEASURING SYSTEMS*

Optical 3D measuring systems are widely used to determine the geometric properties of objects from 2D photographic images and, more specifically, to obtain 3D Cartesian coordinates of a series of points on an object. One area in which this type of device is particularly useful is in the field of biomechanics, in which the movement of humans is studied. Typically, the optical reflectors are placed on articulations and segments of interest. They then track, in real-time, the kinematics and dynamics when performing a given task, such as walking. Other common fields of applications are aerospace, automotive, robotics, and non-destructive testing (NDT). High-quality optic systems are also ubiquitous in the field of QC inspections. In fact, these systems can be used alone to perform very accurate measurements; however, they are more often used within nearly complete probing or 3D scanning measuring solutions. Indeed, the applications of optical

3D measuring systems are limited to measuring and tracking the Cartesian coordinates of optical references that are placed on a part.

#### *1.5.1.1. OPERATING PRINCIPLES OF OPTICAL 3D MEASURING SYSTEMS*

The configuration of optical 3D measuring systems usually consists of two or three cameras simultaneously acquiring images, at high frequencies, to obtain different views on a scene. With these systems, it is possible to directly measure or track optical reflectors using triangulation as the distance(s) between the sensors is already known (these distances are called baselines).

Triangulation is the process of determining the location of a point by measuring angles to it from known points at either end of a fixed baseline. The point can then be fixed as the third point of a triangle with one known side and two known angles.

This principle of optical 3D measuring systems can be considered as slightly different than photogrammetry (see *Photogrammetry* section) for two main reasons. First, measuring devices using high-quality optic systems usually include two—or a maximum of three—cameras that are oriented in the same direction and with a known baseline. Second, photogrammetry generally involves pictures taken from different positions and orientations with respect to the object that is of interest (where the relative positions of the camera are unknown beforehand). Typically, photogrammetry systems involve taking more than two pictures of the same optical reflector to ensure an appropriate convergence since each picture does not result from a smoothed average of several pictures taken at a high frequency (which is usually the case for optical 3D measuring systems).

#### *1.5.1.2. CREAFORM'S C-TRACK AND VXTRACK*

Creaform's C-Track device and the VXtrack module of the VXelements software consist of an optical 3D measuring system that allows the simultaneous measuring of a set of reflectors. This complete portable 3D measuring solution offers very good dynamic measurement capabilities as it enables users to perform six degrees of freedom tracking of objects in real-time (recording and display in VXelements). In fact,

both camera sensors of the C-Track simultaneously acquire images at a high frequency. Furthermore, the triangulation of rigid sets of reflectors that are secured on the part that is of interest is performed in real-time using sophisticated algorithms. Although this measuring system is used in a very wide range of fields and applications, such as calibrating and assisting robotic equipment, sheet metal warping analyses (deformation's monitoring), movement monitoring on running parts in automotive manufacturing, etc. its main purpose can be summarized as capturing the in-space behavior (kinematics and/or dynamics) of physical elements. Creaform's HandyPROBE and MetraSCAN 3D use this principle to simultaneously track the probing/scanning device and the part to inspect in order to group all the data in the same referential and initiate the 3D reconstruction of the desired elements of the part.

#### *1.5.2. NON-CONTACT TECHNOLOGIES (3D SCANNING)*

A 3D scanner is a device that analyzes a real-world object to capture its shape. The collected data is then used to construct a digital 3D model.

Although 3D scanners are mostly used for industrial design, reverse engineering, and prototyping, several QC applications require the use of such devices to perform inspections. 3D scanners allow the inspection of a part without having to make any physical contact on it. Also, applications requiring a high density of measurement data, such as when a surface profile GD&T needs to be computed, should make use of 3D scanners as they allow the measuring of a very high amount of data in a very effective way.

##### *1.5.2.1. OPERATING PRINCIPLES OF SCANNING DEVICES*

There are several types of 3D scanning technologies that use completely different principles. They are grouped into two main categories: active scanners and passive scanners. Each category includes several technologies to achieve the 3D digitization; however, only the relevant ones, for QC or inspection applications, are described here. Each technology has distinctive features, but the global workflow is the same for 3D scanning devices (Figure 13).

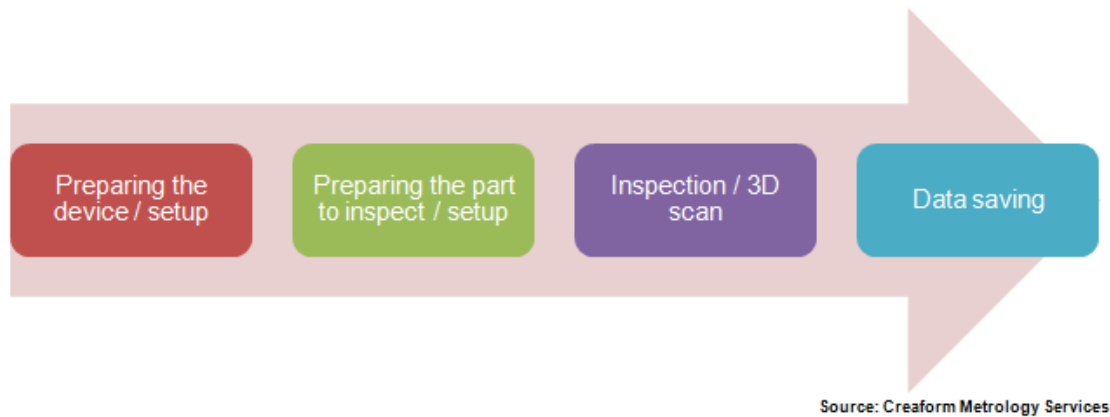


Figure 13: Representation of workflow of 3D scanning.

#### 1.5.2.2. CREAFORM'S METRASCAN 3D

Among all the available 3D scanning technologies, the most suitable for QC purposes is Creaform's MetraSCAN 3D, which uses high-quality optics to locate the scanner position in respect to the part (both are tracked at the same time by a device including two cameras called C-Tracks) and perform the actual measurements on the part.

The MetraSCAN 3D projects a laser cross on the surfaces of the part that is observed by two dual sensors, which are mounted on the scanner to record the data. In other words, the principle of triangulation is used to locate the scanner and part as well as to take measurements. Therefore, the accuracy of this scanner is not affected by environmental conditions, such as vibrations. Moreover, this solution offers a very high volumetric accuracy. In addition, the acquisition software provided with the scanner includes powerful algorithms to optimize the quality of the scan. Also, the system is completely portable and very user-friendly.

#### 1.5.3. PROBING (CONTACT TECHNOLOGIES)

Probing technologies are the most widely used solutions in the industry as they are well-known and established. All probing devices include a stylus or a probe, which makes actual contact with the part to measure it.

Except for point probes, the tips of the probes have spherical shapes with highly accurate diameters. A probe or a stylus can have different lengths and diameter values; they can even include elbows. Each measuring device has its own calibration procedure that characterizes these parameters before undertaking any measurements.

Probes are always manufactured with very stiff materials (the tip and extension) in order to reduce deflections during measurements as they are not detected by the machine, which, in turn, increases measurement uncertainty. It is obvious that the longer the probe, the more it will bend while making contact with the part.



Source: [www.directindustry.fr](http://www.directindustry.fr)

Figure 14: Stylus and probes examples.

#### 1.5.3.1. OPERATING PRINCIPLE OF PROBING DEVICES

The operating principle of probing devices is quite simple. However, it involves an understanding of several engineering and metrological concepts. There is a variety of contact technologies that use completely different approaches. Indeed, there is a wide range of measuring device types, mainly due to the fact that QC applies to a very large spectrum of applications involving the inspection of different part sizes and types. However, the main purpose of all probing devices remains the same: accurately record the 3D Cartesian coordinates of a single point at a time.

The most important principles to understand, while performing inspection by probing, are the concepts of aligning the measuring machine on the part and compensation of the probe.

The first concept on alignments consists of performing transformations on the measurement data to express it in a desired coordinate system. Indeed, before performing any alignment, the measurement data is expressed in the coordinate system of the machine, which is, most of the time, not useful to extract relevant information from measurements. In fact, the need to perform an alignment is dictated by the requirements of the inspection.

Although metrology software programs include several alignment techniques, the main principle remains to superimpose measured features with their respective nominal values to find the proper transformation to apply on measurements. Moreover, if a 3D CAD model is used as a reference object in the inspection program, performing an alignment will allow the user to directly express the measurement data in the coordinate system of the CAD as well as perform efficient and sophisticated comparisons with it, such as the recording of comparison points or computation of complex GD&T. On the other hand, it is possible to perform alignments without using any CAD models. In this case, a new coordinate system is created at a specific location from which the measurement data is expressed.

The other important concept exclusive to probing technologies is regarding the compensation of the probe's diameter. Indeed, measuring devices are only able to record the center of the probe; however, usually the main interest is the actual point of contact with the surface of the part. Acquisition rules must therefore be followed to ensure the computation of desired elements while probing. Probing a hole or a pin requires the exact same manipulations. However, the computer needs to know on which side to compensate the diameter of the probe in order to obtain the desired diameter. The same principle applies for most geometric features.

Regarding the probing of comparison or surface points, the measuring device must be aligned on the part since the direction of compensation is dictated by the closest



surface of the 3D CAD model. For most measuring devices, the software usually uses the orientation of the probe to determine the compensation side.

#### *1.5.3.2. TRADITIONAL PROBING COORDINATE MEASURING MACHINE (CMM)*

Traditional CMMs are the most widely used solution in QC applications, mostly because they have been used in the industry much longer than portable CMMs. Moreover, they generally lead to a more accurate inspection (higher volumetric accuracy).

Traditional CMMs have several weaknesses, such as their non-portability and high acquisition costs. They also have a smaller (and not expandable) working volume, which implies a limit in the size of the measured parts.

Another particularity in their functioning is that they need to be specifically programmed, because the movements of the device are automated. Preparing the inspection routines enables the machine to work on its own. Nevertheless, the entire process is generally time-consuming. Therefore, traditional CMMs still need human intervention to work, despite the level of automation they offer.



Source: [www.mitutoyo.com](http://www.mitutoyo.com)

Figure 15: Mitutoyo coordinate measuring machine (CMM).

#### 1.5.3.3. PORTABLE PROBING CMM - GENERAL

Portable CMMs bring new possibilities to companies, offering unprecedented QC services by allowing on-site inspections. Moreover, portable CMMs in QC applications also greatly contribute to the inspection of large parts that cannot be measured with traditional CMMs.

There is a variety of technologies that fall under these types of CMMs. The most common solutions found in the industry are laser trackers, measuring arms, and high-quality optic systems.

There are several advantages to portable CMMs. They are often more affordable than traditional CMMs. They involve less annual costs and shorter training periods. Finally, help users to perform fast inspections. Moreover, since they are portable, the device is usually moved to the part to inspect—instead of moving the part to the machine. It is worth mentioning that portable CMMs also enable users to inspect the same part from different points of view while expressing all the measurement data in the same coordinate system. This useful characteristic allows portable CMMs to extend their working volume to measure parts of any size.

Each time a measuring machine is moved to a new location, references with known coordinates (taken from the first position) must be re-measured to track the displacement of the device. This principle is called *leapfrog* and is widely used in the industry. A drawback of using leapfrog to move an inspection device is that the accuracy of the operation depends on the quantity and positioning of references. Indeed, the metrologist must be aware that an incorrect distribution of the references (with respect to the part and with respect to each other) will have a direct impact on the measurements.

In practice, the distribution of references should cover the space in three orthogonal directions and should, as much as possible, encompass the location where the measurements are taken. A type of reference that is widely used in the industry is

called *tooling balls*, which consists of hard spheres having their diameters manufactured with a very high level of accuracy. Another very common type of reference is called *spherically mounted retro-reflector* (SMR), which is generally used within laser tracker technologies. Finally, for optical solutions, such as Creaform's HandyPROBE, these artefacts are not mandatory as highly reflective targets can also be used as references.

#### 1.5.3.4. PORTABLE PROBING CMM – LASER TRACKERS

Laser trackers are considered as accurate portable CMMs solutions if they are used in a vibration-free environment and a rigid link is ensured between the device and part to measure (which is, most of the time, not the case). Also, the volumetric accuracy of these devices usually decreases (measurement uncertainty increases) inversely proportionally with the distance of the measurements.

Laser trackers generally use the technologies of interferometer measurement (IFM), absolute distance measurement (ADM), or a combination of both to estimate the radial distance of a reflector, which is usually a spherically mounted retroreflector (SMR).



Source : <http://www.apisensor.com.br/>

Figure 16: Laser tracker.

IFM technology usually estimates distances using wavelengths of light, from which the light source is sent from a helium neon laser emitted by the laser tracker. This technology requires an initial known position of the reflector (often called the home position) and does not keep on measuring if the beam is interrupted (by an obstacle, for instance).

ADM technology is based on a repetitive time-of-flight technique to estimate distances. An SMR is a sphere made of stainless steel that has a diameter manufactured with a high degree of accuracy and three triangular shaped mirrors that are inserted in a symmetric manner having one common apex at the exact center of the sphere. The azimuth and elevation angles are measured with the encoders of the servomotors, which compute the 3D Cartesian coordinates of a point with respect to the origin of the device.

The SMR, which is the actual probe of the device, is usually held by the user. However, it can also be placed on specific locations using magnetic nests. In the

same manner as other probing devices, the SMR is moved in contact with the surface of the part in order to take the measurements. Once the laser beam emitted by the machine is directed to an SMR and reflected back to the machine, the automatic tracking starts. This means that any relative movement between the machine and the SMR will imply a movement of the laser beam to maintain the SMR's tracking. Therefore, the servomotors of the device are controlled simultaneously using the concept of a PID controller built in the system so as to ensure a smooth and quick response tracking. Usually, the laser tracker and the part to inspect are fixed; the user moves the SMR to specific locations on the part to record the measurements. This useful feature allows moving the probe (SMR) all around the part without needing to manually redirect the laser beam between each desired position. The user holding the SMR must keep its open end directed through the machine (within an acceptable threshold). The line between the SMR and laser tracker head must also remain free of obstacles; otherwise, the tracking will stop.

Regarding the acquisition rules related to the compensation of the probe (SMR), they are slightly different for laser trackers as this technology only tracks three degrees of freedom, rather than six in the case of other devices. Unlike other probing systems, the probe (SMR) has no orientation, only the 3D Cartesian coordinates are recorded. In these situations, each metrology software has its own solutions to determine the compensation direction. However, one extra point usually has to be recorded at the end or beginning of the probing process in order to simulate the orientation of the probe. When probing of a hole, for instance, the extra point will be recorded at the inside of the circle to provide the appropriate information to the software. It is obvious that compensation rules do not apply if a point probe is used instead of a ball probe: the recorded point always corresponds to the contact point on the surface of the part.

#### 1.5.3.5. PORTABLE PROBING CMM – MEASURING ARMS



Source: [www.hexagonmetrology.com](http://www.hexagonmetrology.com)

Figure 17: Articulated portable probing arm.

A measuring arm is also widely used for many QC applications. It is considered as a very efficient alternative. The reason: it helps to take measurements very quickly and in a very convenient way. This solution is also considered to be quite accurate (a little less than laser tracker)—as long as the device and part to measure form a rigid body.

Moreover, the volumetric accuracy of a measuring arm is not uniform throughout its working volume. Indeed, this specification relies on the resolution of the encoders at each articulation of the arm (an arm is usually provided with 6 joints). Therefore, the more the measurements are taken away from the basis of the arm, the less the articulations of the arm will have to rotate (for the same displacement of the effector), which results in an overall lower resolution. Regarding the working volume of a measuring arms it is quite small compared with other portable CMMs; it is therefore often required to reposition the device (performing leapfrogs) at several locations to complete the inspection.

Unlike laser trackers, the movements of the probe are tracked using six degrees of freedom as the orientation of the probe is also known and taken into account for compensations. In fact, these devices can be associated with robotic arms (without having any actuators) as they have a similar configuration and use the same mathematical concept to determine the position and orientation of the end effector (which corresponds to the probe in this case). Indeed, determining the position and orientation of the end effector of a robotic arm, knowing the rotations of each joint consist in solving to the well-known direct kinematic problem (DKP). Using the *Jacobian* matrix<sup>10</sup> that corresponds to the configuration of the measuring arm, these computations occur in real-time, which allow tracking the movements of the arm in a very efficient and accurate way.

#### 1.5.3.6. PORTABLE PROBING CMM – PROBING DEVICES USING QUALITY OPTICS

The principle used by the 3D optical measuring systems described in section 2.5.1 is used to track the probing device with the use of optical reflectors that are placed on it. Indeed, triangulation can be used in order to locate a probing device in space. These technologies generally lead to very flexible solutions as the probe is directly attached on a small, lightweight, and usually wireless device that can easily be handled by the user.

#### 1.5.3.7. CREAFORM'S HANDYPROBE

Creaform's HandyPROBE (Figure 18) is an arm-free, portable coordinate measuring machine (CMM) that generates high-accuracy measurements (up to 22 µm). This probing device uses high-quality optics to perform the measurements. It is fitted with C-Track dual camera sensors, which enable the device to measure reflectors within their operating spaces. In addition to tracking the reference model of the whole system, the C-Track provides the exact localization of the HandyPROBE (using triangulation), performs continuous image acquisition and transmission, ensures that the reflectors are lit, and manages both the interfacing with the computer and storage of the sensor parameters.

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<sup>10</sup> URL: [http://en.wikipedia.org/wiki/Jacobian\\_matrix\\_and\\_determinant](http://en.wikipedia.org/wiki/Jacobian_matrix_and_determinant)



Source: Creaform Metrology Services

Figure 18: Creaform HandyPROBE.

A great advantage of probing devices using high-quality optics, such as the HandyPROBE, is the total freedom of movement the user experiences while inspecting a part (Figure 19). Indeed, unlike most CMM solutions, no rigid link is needed between the part to measure and the measuring machine. This interesting feature increases the reliability and speed of the measurement process, which results in a significant increase in productivity and quality. Moreover, the volumetric accuracy of the system is not affected by environment conditions, such as vibrations, since all the relative movements between the part and machine are tracked and recorded at a high frequency.



Source: Creaform Metrology Services

Figure 19: Creaform HandyPROBE in action.

The HandyPROBE is generally used for measuring geometric entities in small- and medium-sized parts. The device can additionally measure large parts, but it is



recommended to use the benefits of photogrammetry with Creaform's MaxSHOT 3D to generate more accurate 3D positioning models.

#### *1.5.4. PHOTOGRAMMETRY*

Photogrammetry, or more specifically stereophotogrammetry, determines the geometric properties of objects from 2D photographic images. More specifically, it is used to obtain 3D coordinates of points on an object. This technology is a useful and powerful tool to accurately measure individual points on a part, but like optical 3d measuring systems, it is usually not used alone to perform a complete inspection since its application is limited to measuring the Cartesian coordinates of optical references. Therefore, photogrammetry is a complementary tool for some probing and scanning technologies as it allows measuring specific references on an object, with a very high degree of accuracy.

As described earlier, photogrammetry devices differ from optical 3D measuring systems in that they record a single picture at a time and generally involve a high number of points of view that observe the same point.

##### *1.5.4.1. OPERATING PRINCIPLE OF PHOTOGRAMMETRY*

The 3D coordinates of points on an object are determined by measurements carried out using usually more than two photographic images taken in different positions and orientations. Common points are identified on each image and a line (radius) can be constructed from the camera position to the point on the object. It is the intersection of these radiuses (triangulations) that determines the 3D position of the point.

##### *1.5.4.2. CREAFORM'S MAXSHOT 3D*

The system combines the MaxSHOT 3D photogrammetric video camera (Figure 20) and VXshot processing software. Using this solution, Creaform probing and scanning devices can benefit from photogrammetry to construct a more accurate dynamic referential model, which consists of optical reflectors that are placed all around the part to reference the C-Track.



Figure 20: Creaform MaxSHOT 3D.

Photogrammetry is usually used when inspecting large parts, or when references need to be placed on both sides of a part, in order to obtain more accurate 3D positioning model of targets. Photogrammetry is also used to characterize the volumetric accuracy depending on the object size. Indeed, using the MaxSHOT 3D along with most Creaform devices (HandyPROBE, MetraSCAN 3D, HandySCAN 3D, and the Go! SCAN 3D) enables users to compute the volumetric accuracy with respect to the size of the part as each device has its own simple formula. Moreover, the 3D average uncertainty (standard deviation) of the target's position is provided once the high-accuracy positioning model is computed. Individual statistical information is also available for each target, which allows the user to interactively refine the model.

This photogrammetry solution uses sophisticated algorithms that take into account information that is known beforehand, such as scale bars and coded targets, to increase the performance and ensure the convergence of the positioning models.

## 1.6.METROLOGY SOFTWARE

Along with recent innovations in inspection devices, metrology software has revolutionized the industry: the inspection process has become extremely more accurate and efficient—and ultimately significantly impacted the global economy. Moreover, these recent advancements have brought several new possibilities in metrology by allowing the control of new features that could not be measured beforehand, such as the computation of complex GD&T surface profiles. Metrology software now has an important role in Total Quality Management (TQM) as it is widely used in design, production, and QC all over the world.

### *1.6.1. DEFINITION*

Metrology software is a computer platform that allows CMM users to prepare and achieve their inspections. This software also helps users to organize, manipulate, and execute operations on measurements in order to perform GD&T analyses on real physical elements with the use of reference objects (such as CAD models).

Most metrology software offers the possibility to generate reports in a rapid and efficient way. Some metrology software is also widely used for reverse engineering, such as building clean and parametric CAD models from raw scanned data. Also, measurements of CMMs are generally directly taken via metrology software, using equipment plug-ins.

### *1.6.2. AVAILABLE SOLUTIONS*

In the industry, the current, most important metrology software with regards to scanning and probing technologies are:

- ▶ PowerINSPECT (Delcam)
- ▶ PolyWorks (InnovMetric)
- ▶ Metrolog X4 (Metrologic Group)
- ▶ Control, Studio, Wrap (Geomagic)
- ▶ Geomatic Design X, Geomagic Verify (Rapid Form)
- ▶ Quindos (Hexagon)
- ▶ MobiGage (NDI)
- ▶ Spatial Analyzer (New River Kinematics)
- ▶ Verisurf X6 (Verisurf)
- ▶ Calyspo, HOLOS NT (Zeiss)
- ▶ BuildIT (BuildIT Software & Solutions)
- ▶ Inca 3D (Inspect 3D)
- ▶ Metrosoft CM (Wenzel Metromec)

Each software solution has its own strengths and weaknesses. Most perform GD&T analyses with powerful automated calculations that respect the criteria of the ASME Y14.5 standard. This is an important fact to know since, most of the time, the user is not clearly aware of the calculation methods used by the software.

### *1.6.3. UTILITY AND APPLICATIONS*

The main purpose of metrology software is to provide the user with a useful tool to manage the inspection sequence. It also acts as a platform with which measurement data is taken and managed and operations are performed to efficiently report on desired elements. Moreover, some metrology software includes useful tools for reverse engineering applications, such as CAD reconstruction from raw polygonal models. Also, metrology software generally offers very useful means to manipulate 3D models, particularly regarding the extraction methods of feature types on CAD or polygonal models. Most of the available metrology software on the market perform basic and advanced GD&T calculations. In addition, solutions also use several alignment techniques with powerful algorithms, which enables users to quickly superimpose data measurements with a reference object and perform comparisons. It is also very convenient and efficient to report the desired elements resulting from an inspection using most types of metrology software. Typically, an inspection report includes tables of features and comparison points that display tolerances and deviations, along with snapshots, to be able to locate the elements of the tables on the part.

## 2. QUALITY CONTROL TECHNOLOGIES: THE PRACTICE

Inspection techniques and measuring instruments involved in QC can vary a lot, depending on the part to be inspected and requirements. Indeed, the two main aspects of QC, namely product features and freedom from deficiencies (compliance), have different purposes and aim at controlling completely different things on a part. Elements of interest can vary from function and performance, design configuration, ease of use, and aesthetic appeal when QC is implemented in a design process. The absence of defects, compliance to specifications, and ensuring components remain within tolerances are considerations that are more important when QC is part of a manufacturing process. Therefore, it is of the utmost importance to clearly understand customer needs before undertaking an inspection process.

Even though the spectrum of QC applications is very large, the typical workflow for inspecting any part, for any reason, does vary that much. In fact, the two main distinct inspection technologies, scanning and probing, generally lead to small differences within the workflow. As previously defined, 3D scanners inspect a part without having to make any physical contact with it, unlike probing devices. Both solutions have advantages and disadvantages, depending on the application. In other words, they are complementary solutions. Since the operating principles are very different and they are sometimes used for different purposes, these two techniques differ depending upon the various stages of the inspection workflow. Despite these differences, the common main steps are:

- ▶ Gather information
- ▶ Choose the equipment and software
- ▶ Prepare the software
- ▶ Prepare the hardware
- ▶ Measure the part
- ▶ Manipulate the data and extract relevant information
- ▶ Generate report

### 2.1.GATHER INFORMATION

The first step of the workflow of any QC process is to understand the main objective of the inspection. In other words: what needs to be measured and why. It is often very important to understand the functional purpose of a part and its main features, particularly if the part is used in a manufacturing process or being manufactured, to make good decisions before undertaking the inspection. The technical requirements are generally provided by the customer as drawings and CAD 3D models. Depending on the requirements, one specific metrology software might have to be prioritized (when possible) if, for instance, complex GD&T calculations are required. Each metrology software solution has pros and cons, and again, depending on the context (if several software solutions are available), the metrologist will have to find the most suitable software to perform the inspection in an efficient way.

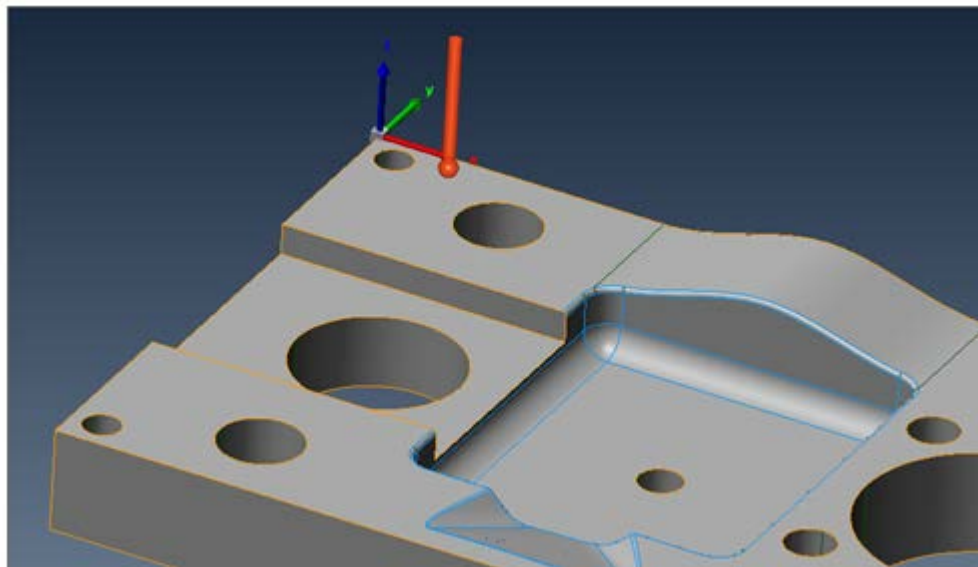
It is often necessary to speak with the client to make sure that technical requirements are interpreted correctly. Even if well-known rules and standards are established with respect to engineering drawings and design, companies do not always follow them. Therefore, it is ideal to have a candid conversation with the customer to fix the objectives of a mandate and clarify all technical details.

Having an idea of the magnitude of tolerances required by the customer is very important since it will have a direct impact on the choices of equipment and inspection techniques employed by the metrologist. Important information, which is often hard to get from the customer at the early stages of a project, is to know where the part is going being inspected. Relevant environment information includes vibrations, temperature, temperature stability, available space around the part, and whether it is a dusty environment or not (mostly for optical solutions, such as Creaform's HandyPROBE). This information will also guide the metrologist in the choice of equipment to perform the inspection tasks.

## 2.2.PREPARE THE 3D CAD MODEL FOR THE INSPECTION

Depending on the application, the inspection might require the loading of a 3D CAD model in the inspection program of the metrology software to act as a reference object. For instance, this is necessary when profile or location GD&Ts are required. Indeed, the resulting measured zones, to be compared with the given tolerance zones, are computed by the metrology software with algorithms that use a reference object from a 3D model. Also, importing a CAD is necessary when comparison points have to be used. This is important, for instance, when

comparing the deviation between the real part and the CAD in a given alignment—and at specific individual locations on the part. Moreover, some alignment types that use a reference object require a 3D model, such as alignments of type “best-fit.” Even if an alignment can be performed without a 3D CAD model, it is always useful to have visual feedback on the 3D scene of the metrology software to verify that the alignment has occurred correctly. For instance, it is important to look at the location of the virtual probe with respect to the CAD on the 3D scene by bringing the real probe of the device at specific locations on the real part. Importing a 3D CAD model in an inspection program is also very useful to directly affect nominal values (reference values) to feature objects simply by picking them on the 3D scene, which is much more efficient than entering all of them manually.



Source: Creaform Metrology Services

Figure 21: The virtual probe shown on the part to verify that the alignment has occurred correctly.

For inspections using a 3D CAD model, it is preferable to load it in a CAD or metrology software at the early stage of preparation, before undertaking the inspection, to validate its content and ensure it can be used adequately to perform the measurements.

A first example of an undesired element that can be found in the CAD model provided by the customer is an inconsistency between the coordinate system of the CAD model and the 2D drawing. This occurs very frequently when the piece to inspect is part of an assembly in which the coordinate system of the part is the same as the one for the entire assembly. Indeed, it is

sometimes necessary that the orientation of the coordinate system of the CAD fits with the views displayed on the 2D drawing. This is particularly true when distances in specific directions are required (for instance, in the same direction as the x-axis). In this case, performing an alignment of the measurement data on the reference object would lead to an x-distance that makes no sense, since the x-axis is not in the right direction on the CAD with respect to the 2D drawing. It should be noted that this problem does not occur if only 3D distances are required. Another case in which the coordinate system must fit between the CAD and the 2D drawing is when performing an alignment of the measurement data on the reference object that requires to individually specify the directions of alignment of each item part of the alignment, namely x, y and z. Therefore, if the coordinate system of the CAD must be transformed to concur with the 2D drawing, most metrology software programs enables users to do it—but sometimes in a more inefficient way. Note that this operation can also be performed using any CAD software and before importing the model in the metrology software.

Another example of manipulations that might have to be performed on the 3D CAD model prior the inspection is to clean it by removing unnecessary surfaces that will not be used for the inspection. This reduces the risk of measuring the wrong thing and facilitates the inspection process. This can be done directly with most metrology software during the inspection; however, it is more efficient to perform this operation prior to the inspection, using CAD software that provides much more CAD-handling tools.

## 2.3.CHOOSE THE RIGHT EQUIPMENT

It is obvious that this stage of the inspection workflow is only relevant to users that have access to several technologies. Otherwise, no choice has to be made; this stage of the workflow is therefore requires users choosing the most efficient way to inspect the part with available equipment. Therefore, it is important to mention that, most of the time, any measuring device and metrology software can be used to perform an inspection on a part; it is only a matter of choosing the most efficient solution that proves a level of accuracy acceptable for customer needs. For example, measuring with a too high a level of accuracy is not necessary and can be time consuming.

Once the information regarding the inspection requirements is gathered, the next step is to think about the setup of the CMM and the part. In order to choose the appropriate measuring



device to perform the inspection, the following elements should be considered: required hardware for the setup, inspection environment conditions, size of tolerances, geometry (length, height, concave surfaces, obstacles, etc.), the specific characteristics (weight, stiffness, etc.) of the part to inspect, the number of operators available to perform the inspection, and the available time to perform an inspection.

Regarding the environmental conditions, if there are a lot of vibrations in the area where the part is inspected, they will very likely affect the results and increase measurement uncertainty. This is true with most inspection devices as a rigid link is required between the machine and the part to ensure a good accuracy. Indeed, as soon as any relative displacement occurs between the machine and the part, measurement uncertainty increases substantially. It is, unfortunately, very hard to estimate relative displacement. Under these conditions, Creaform's HandyPROBE should be used, since the measurements taken with this device are not affected by vibrations. As previously described, the dynamic referential built on the part is constantly observed by the C-Track at a high frequency in order to detect any relative movement between the part, HandyPROBE, and C-Track.

For situations where the part to be inspected is relatively large, using a measuring arm is not an ideal solution as it requires a lot of time-consuming machine displacement (leapfrogs), which gradually increases the measurement uncertainty at each displacement. Therefore, laser tracker technologies or Creaform's HandyPROBE are more appropriate in this case. Also, if the part to measure includes several obstacles, laser trackers might not be suitable since the laser beam has to be free of obstacles to take the measurements. This means that it is very likely that the device has to be repositioned several times to new locations to be able to measure all the desired elements on the part. Once again, such leapfrogs imply a loss in accuracy—and a loss in time efficiency as the laser tracker has to be secured with care at each new positions. Therefore, Creaform's HandyPROBE is the go-to solution as it is a lot more flexible. Indeed, no rigid link is required between the C-Track, HandyPROBE, and the part to perform the measurements. Moreover, depending on the application and desired level of accuracy, photogrammetry can also be used, along with Creaform's HandyPROBE and MaxSHOT 3D, to increase the accuracy of the 3D model of references.

If there is a very high number of required surface or comparison points to measure on the part, for instance when a surface profile GD&T is required on a part using a high density of

measured data points. In this situation, it can be time consuming to use conventional probing devices; scanning technologies should be prioritized. Indeed, 3D scanners help to measure a very high amount of data in a very effective way. Creaform's MetraSCAN 3D is a very good alternative since it includes all the same benefits of the HandyPROBE (as it uses exactly the same technology), while offering the exact same volumetric accuracy.

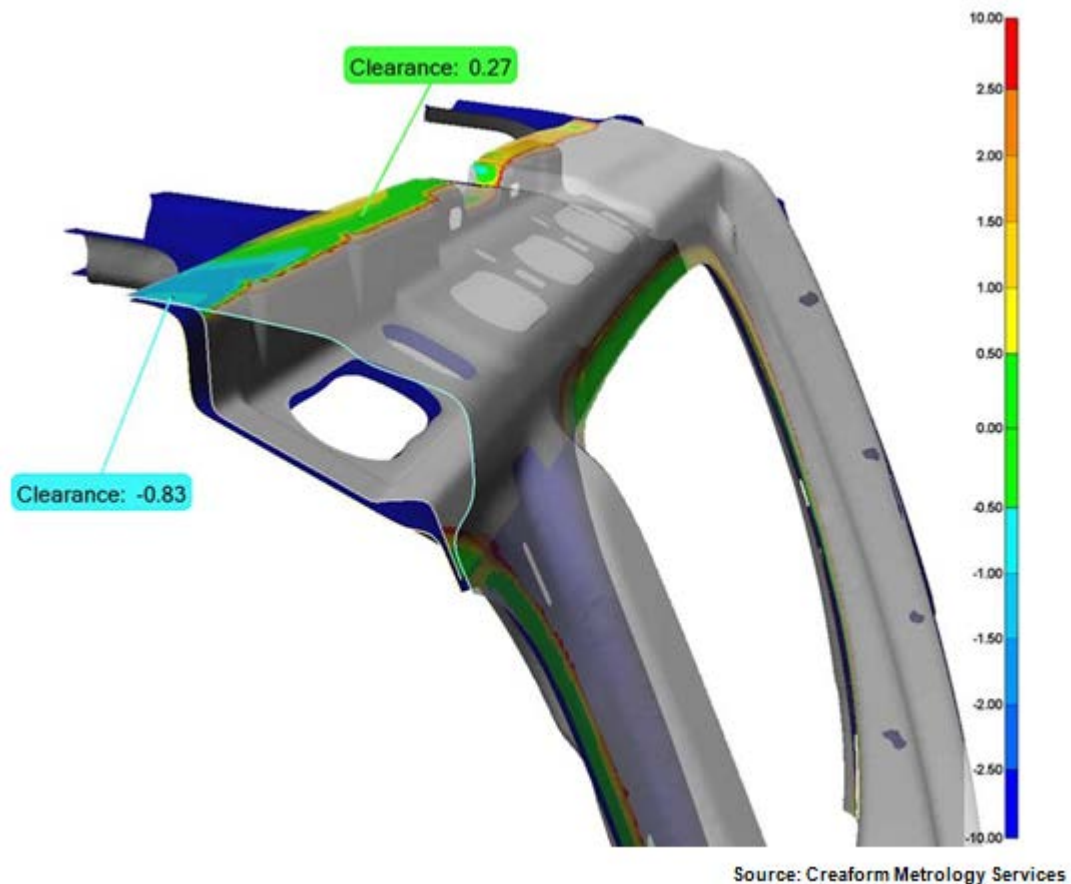


Figure 22: Surface profile of a scanned part presenting much more data than traditional inspection.

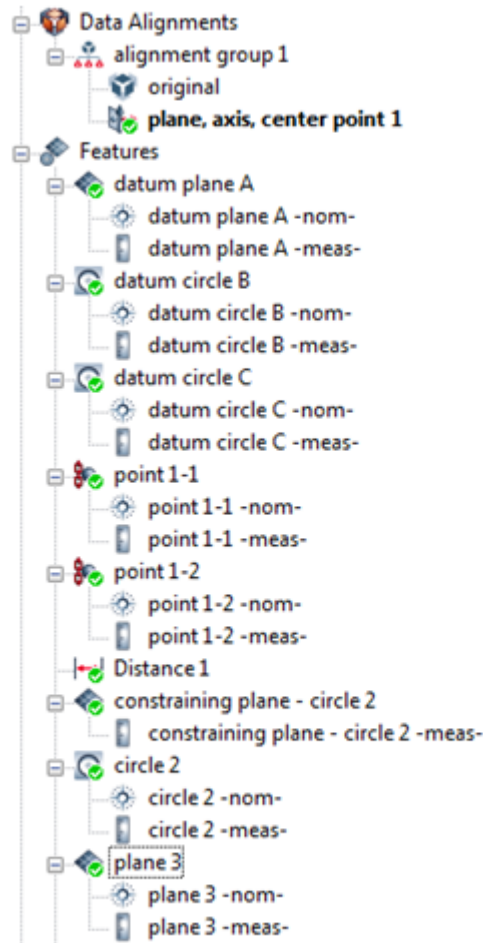
For applications in which very high level of accuracy is required, for instance 50 microns (0.002 inch) and fewer, the use of portable CMMs might not be suitable; more accurate solutions should be used, such as traditional CMMs or optical comparators.

A part of the equipment that should also be chosen adequately, depending on the application, is the metrology software. In fact, every metrology software has its own pros and cons and, depending on the features to measure on a part, one solution can be much more suitable than another for a specific application.

## 2.4.BUILD THE INSPECTION PROGRAM

Once the equipment is selected, the next step is to build the inspection program within the metrology software to prepare for the inspection. This step is often very useful to ensure the inspection sequence and program data management to automate the various computations required to extract relevant information. This can be very useful, for instance, to provide on-site feedback to the customer as soon as the measurements are taken. Another advantage of building the inspection program prior to the inspection is to save time and report the results in a very effective way. This step of the workflow ensures that customer requirements are scoped with care so that the right information is reported. It may be necessary to discuss technical requirements with the client and how results should be received. A good example of the need of discussing with the client prior to the inspection is when the metrology software used includes some limitations that can affect the deliverable.

Building the inspection program consists of importing the reference object (CAD) as well as creating or building the various required features. The nominal dimensions of the feature objects are generally directly picked on the CAD. The good tolerance values are associated to each dimension being reported. Distances and GD&T can also be computed from features and will be automatically generated once the measurements are recorded. It is important to mention that most metrology software enable users to construct features from other measured features, as is the case when it is not possible to measure the desired feature. Most metrology software creates alignments in the inspection program before having measured anything. This is also a very useful feature as it allows the user to simply conduct the inspection as it has been programmed—while on-site and without the need to program anything. The final steps for building the inspection program are to manipulate the elements that will be measured (rename the relevant items and create table with the results, etc.) and prepare the snapshots that will be part of the report.



Source: Creaform Metrology Services

Figure 23: Representation of the sequence tree of an inspection program showing the nominal features picked on the CAD and the measured features.

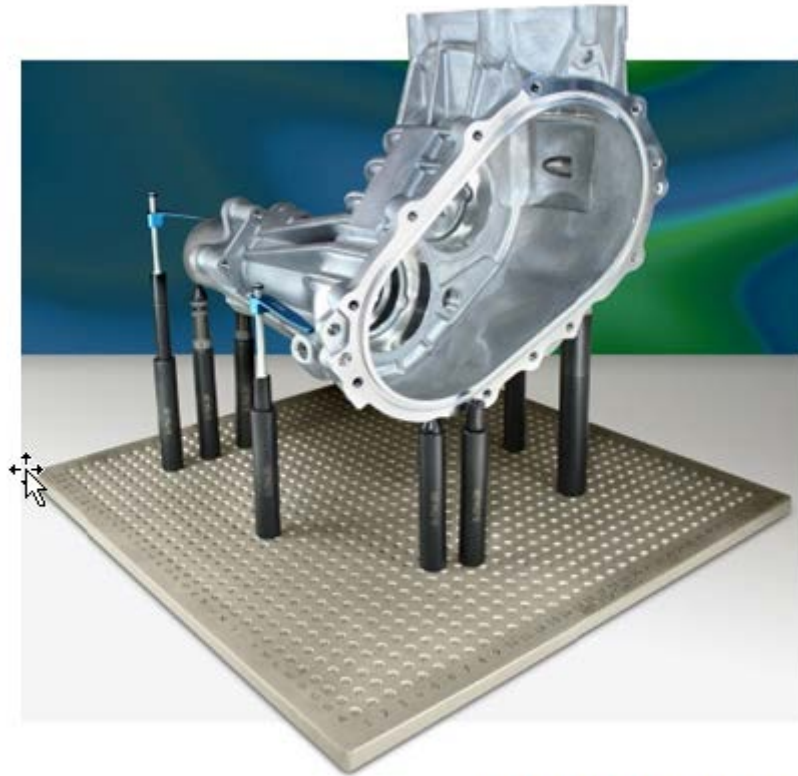
For QC purposes using scanning technologies, the level of automation that can be obtained within the inspection program to process the measurement data is limited, compared with probing inspection. This can be explained by the fact that the desired features (a circle or a plane for instance) must be extracted from the raw data of the scan, which generally implies human intervention in the process to obtain a higher accuracy. Some metrology solutions offer useful tools for automatic extraction; however, the efficiency of these tools completely relies on the quality of the raw data. Creaform's acquisition software, VXelements, includes very powerful and sophisticated algorithms that apply filters and transformations on the data to optimize the quality of the resulting polygonal model.

## 2.5.SETUP OF THE CMM AND THE PART

An inspection setup is a mounting that results from a set of mechanical techniques applied on a part to be inspected and on the measuring device that aims at fulfilling the terms of use of the measuring machine and the inspection's technical requirements. For most inspection devices, this means that the user must find a mechanical way to secure the device and the part so that there is no relative movement between them during the inspection. However, the definition of setup is completely different for Creaform equipment; it allows relative movements throughout the inspection process. Moreover, flexible parts usually lead to more complex setups to adequately constrain the inspection. Therefore, this stage of the workflow varies a lot depending on the measuring technology and the customer's technical requirements. Despite the conceptual differences between the setups using any kind of technology and any type of part, an important fact reside for all cases: the elements of interest to be measured on the part should not be hidden and must remain accessible by the measuring device.

### *2.5.1. TRADITIONAL CMMS (NON-PORTABLE)*

Setups using traditional CMMs are very similar to setups using conventional portable equipment, such as measuring arms or laser trackers: they all attempt to get a rigid link between the machine and the part to measure. However, traditional CMMs have a smaller (not expandable) working volume and generally lead to a more accurate inspection. Therefore, the main difference with portable CMMs is that the machine itself does not have to be secured: the part is directly secured on it. Usually hot glue, combined with mechanical securing techniques, is used to make sure that the part is rigidly fixed on the CMM table. It is obvious that the measurement uncertainty is smaller using these types of devices; however, it also has the inconvenience of having a small working volume, occupying a lot of space, and not enabling portability.



Source: <http://www.apaxmetrology.com>

Figure 24: Representation of a CMM setup.

### 2.5.2. PORTABLE CMMS

Portable CMMS, such as measuring arms or laser trackers, have a very similar definition of setups than that of traditional CMM, except that the device also has to be secured with respect to the part to measure. This is usually achieved using hot glue or magnets. This is why it is important to be aware of the level of vibrations in the area where the part will be inspected; any relative displacement between the machine and the part directly affect the results. Therefore, this type of device has the advantages of being portable and having a very large working volume. The main challenge of finalizing the setup of the part resides in finding a solution to securing the part, ideally on three points, and keeping all elements to measure accessible while ensuring a good rigidity.

### 2.5.3. CREAFORM EQUIPMENT

Creaform optical measuring solutions (probing or scanning) have one significant conceptual difference with other devices: the part to measure does not have to form a rigid body with the inspection device. In fact, it is possible to inspect a part while holding it in a user's hand using Creaform equipment. Indeed, the C-Track constantly observes (at the same time) the HandyPROBE or MetraSCAN 3D—and the optical reflectors that are secured on the part (the dynamic referential). This ensures that the relative movements are tracked and taken into account in the calculations. Therefore, the setup to achieve using such a system consists of securing the optical reflectors on the part, which are usually simple stickers or swivel magnets. It is of the utmost importance that the user clearly understands the rules of building a dynamic referential before using the equipment. These rules can be summarized as follows: there must be enough targets, their distribution should cover the space in three orthogonal directions, and they should, as much as possible, encompass the location where the measurements are taken.

If the part is relatively large or if measurements have to be taken on both sides of a part, for instance, it is possible to perform a volume extension of the C-Track to allow the creation of a single model of reflectors, which are located all around the part. Therefore, the C-Track will be referenced from any point of view with respect to the part during the inspection. The process of creating this model can be performed with the use photogrammetry with Creaform's MaxSHOT 3D to increase the accuracy of the model. In this case, the setup is not different and the same rules apply for the positioning of the targets on the part. It is important to mention that the optical reflectors must form a rigid body with the part to inspect—otherwise, they will not be recognized by the C-Track.



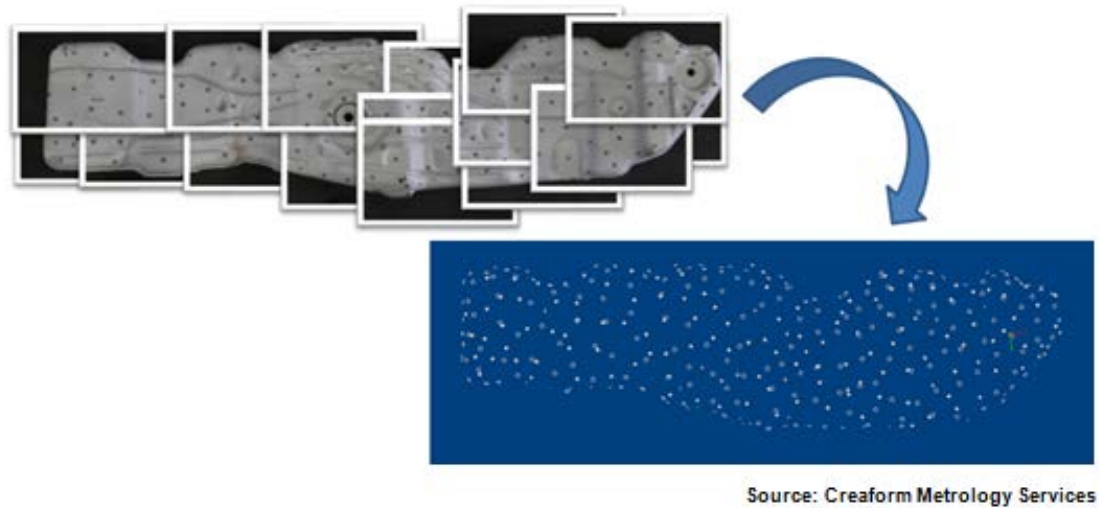


Figure 25: Representation of the photogrammetric model concept.

#### 2.5.4. FLEXIBLE PARTS

Inspecting flexible parts is always a challenge, regardless of the type of measuring equipment used. Indeed, the part must be solidified before starting the inspection in order to simulate the behavior of a rigid body and ensure that all the recorded measurement data can be compared with the same reference object. Moreover, it is often required that the part be inspected in the same configuration as it is going to be used. Sometimes, jigs are used to simulate the real assembly by bending the part to the exact desired geometry. The inspection is then performed once the part is constrained in the jig. However, jigs are not always available as they are expensive to manufacture. For these cases, the requirements are generally provided on a 2D drawing with datum targets that have basic dimensions. These datum targets are used to perform an alignment using specific points on the part and where the relative position of these is prescribed with basic dimensions. This simulates a jig or the real assembly as the part must be constrained in a given configuration. This represents a good challenge as the relative position between the datum targets must fit with the basic dimensions provided in the drawing. In these cases, adjustable mountings (to push and pull at specific locations on the part) must be used to constrain the part to the desired configuration before inspecting it. Another challenge met for this kind of inspection is to leave the areas that are of interest accessible for the inspection device. Typically, hot



glue, screws, and nuts are used to build a setup that rigidly constrains the part to the desired dimensions.

## 2.6.ALIGN THE MACHINE ON THE PART

It is possible to perform an inspection on a part without performing an alignment, depending on the information to be extracted from the measurement. For example, alignment is required so that the distances between the elements are maintained in a specific direction. For instance, an alignment is necessary if distances are required between features in a specific direction.

As described earlier, the inspection might require the use of a CAD model to act as a reference object, for instance if profiles or location GD&Ts are required or if comparison points are used. Therefore, in order to compare the measurements with the CAD, for instance with comparison points, an alignment must be performed on the part. This will allow the user to use the coordinate system of the CAD (instead of the coordinate system of the machine) to express the measurement data—and directly compare it with the CAD values.

Several alignment techniques exist; however, the principle remains the same for all of them. In practice, all techniques consist in measuring the feature objects that are part of the alignment. By superimposing the measured features with their respective nominal from the CAD and following the rules prescribed by the chosen alignment, the software will find the proper transformation matrix (rotation and translation) to apply on the measurements.

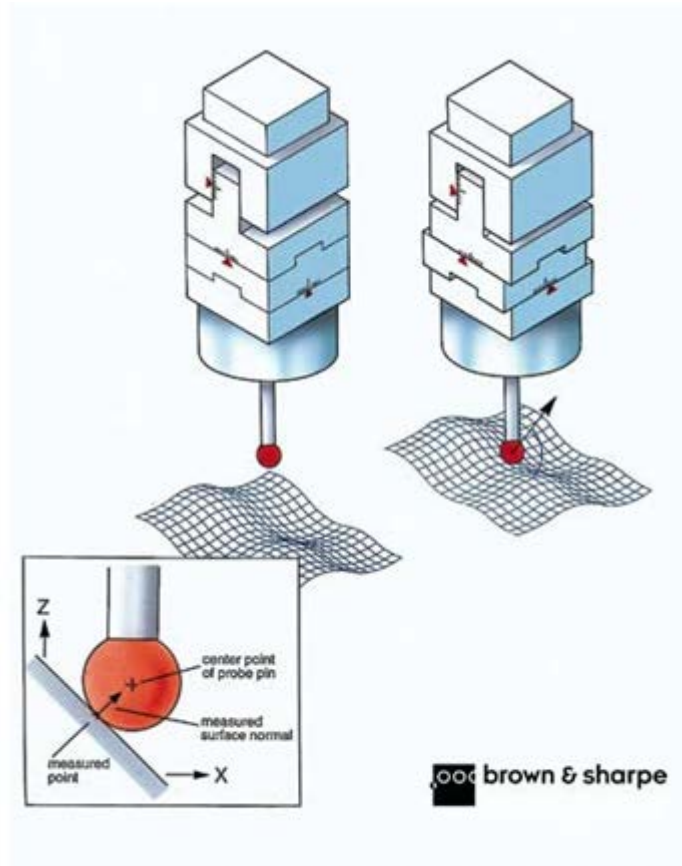
It is also possible to perform an alignment on a part without using any CAD or reference object. Indeed, performing such operation creates a new coordinate system where its location and orientation is defined by the alignment type. This is very useful to express the measurement data with respect to the real part. For instance, it is often useful to define the longest dimension of a part as the x-direction or to place the origin at the center of a hole.

Once the machine is aligned on the part, it is very important to perform a verification to ensure that the software has calculated the desired solution. This validation can be performed in different ways; for instance, a user can place the probe on features of the part that are used in the alignment and view the deviations with the digital readout. All metrology solutions include a

digital readout, which consists of a visual display of the Cartesian coordinates of the center of the probe.

Another method that can be used is simply by looking at the virtual probe on the 3D scene of the metrology software, while moving the real probe to specific locations on the part and verifying the concordance. For instance, if a plane is used as primary datum in the alignment, it should be observed that the virtual probe is almost tangent to this plane (depending on the flatness of the plane). A very common error that is detected while performing such validations is when the compensation of a plane or a line has occurred in the wrong direction.

Regarding scanning technologies, alignment on the part is usually performed when manipulating the data to extract the relevant information, rather than before inspecting the part. Indeed, the data is usually acquired directly in the device coordinate system (that is, the C-Track coordinate system if Creaform's MetraSCAN 3D is used) without performing any alignment. One of the reasons for this difference with probing technologies is that more manipulations are required to extract the features that are part of the alignment using the scanned raw data. Therefore, the on-site time allowed to perform the inspection is generally limited; this is why these operations are, most of the time, performed afterwards. Once again, the level of automation of the inspection program is limited compared with probing devices. Another reason for this difference is that, with 3D scanners, it is possible to measure points all over the surface without being aligned on the part. It is important to mention that with probing technologies, comparison or surface points cannot be measured without being aligned on the part, mainly due to the directions of compensation of the probe. Indeed, probing devices record the center of the probe; however, what is usually of interest is the actual point on the surface of the part. For surface points or comparison points, the direction of compensation is dictated by the closest surface of the CAD model, which cannot be determined if the device is not aligned on the part. However, even though it is less common, it is possible to perform an alignment by probing before undertaking the scanning of the part (for instance by using Creaform's HandyPROBE before scanning with the MetraSCAN 3D). This can be very useful for some applications, because the scanned data will be automatically aligned on the CAD model using the alignment performed with the probing device. This technique is also more accurate if the alignment type uses geometric features.



Source: <http://www.qualitydigest.com/sept00/assets/images>

Figure 26: Representation of the probe compensation.

## 2.7.PERFORM MEASUREMENTS ON THE PART

This stage of the QC workflow consists of taking actual measurements on the part. If proper preparations have been completed beforehand, there should not be many modifications to do on the inspection program at this stage.

Performing measurements on the part can be considered as executing the already planned inspection sequence. The most important things related with this stage are to follow the general acquisition rules as well as the terms of use of the measuring device. Moreover, it is crucial to ensure that all the measurements are recorded before leaving the inspection site. Inspections using a probing device must take care not to damage the part while inspecting it (as this technology requires a contact between the part and the probe). The recording of the

measuring data can take place using different inspection techniques, depending on the application and the elements to measure on a part.



Figure 27: A car frame being measured by the HandyPROBE.



Figure 28: Object being measured by an articulated portable probing arm.

### 2.7.1. PROBING FEATURES

A very common technique to measure data on a part with a probing device is to make use of geometric features. In other words, the geometric features are created at the same time as the measuring data is recorded. Common types of geometric features are: planes, circles, spheres, slots, points, lines, etc. Each type of geometric feature has its own acquisition requirements. For instance, a plane needs at least three points whereas a line only needs two. Usually, more points are recorded to have an idea of the form of the part. For example, this information can be obtained by computing the flatness of a plane, straightness of a line, cylindricity of a cylinder, etc. These are simple forms of GD&Ts that most metrology solutions can compute.

As described earlier, it is important to follow the acquisition rules regarding the compensation of the probe while probing features if a stylus other than a point probe is used. Indeed, the orientation of the probe must be adjusted properly before recording the points, depending on the feature to measure. Otherwise, the computer can choose the wrong solution to compensate. For instance, a hole should be probed while having the vector of the probe pointing toward the inside of the circle, unlike pins that require the probe to point outside of the circle. In this case, if the software chooses the wrong solution to compensate the probe, it would affect the diameter of the circle—but not its center position. While probing a plane, the orientation of the vector of the probe must point toward the same side of the plane as the normal vector of the surface of the part.

The probing of a line is generally necessary to specify on which plane (that has been already probed) it will be constrained so as to project the line on the surface of the part. It should be noted that in this case, the compensation does not necessarily occur in the direction of the constraining plane. Indeed, the user generally decides of the compensation method, which is often to use the orientation of the probe, existing features, or a given standard axis. Therefore, the projection into the plane occurs after the compensation of the probe. It is also possible to probe uncompensated and unconstrained lines if the line does not have to be on the surface of the part.

The probing of standard points (not surface or comparison points) is usually possible to compensate it in one direction (the point remains at the outer surface of the probe),

constrain it in a plane (in this case, the compensation of the probe occurs in the same direction as the normal vector of the constraining plane), or leave it uncompensated. Once again, if the measuring device is a laser tracker, the rules regarding the orientation of the probe for compensation do not apply. Furthermore, the terms of use of the metrology software must be followed.

Once they are probed, geometric features can be used to perform alignments or extract relevant information on the part. More specifically, information regarding the feature itself or its location on the part can be obtained (e.g.: diameters, GD&Ts, etc.). Other information can be obtained, such as distances between features or any other constructed feature that could not be probed directly. For instance, a circle can be constructed by the intersection of a probed sphere and probed plane, or by the intersection of a probed cylinder and a probed plane. A line can be constructed by the intersection of two probed planes and a point from the intersection of three probed planes. This technique of constructing features is also very useful to create middle planes, middle lines, or middle points in order to perform alignments using the center of a pair of entities.

### *2.7.2. PROBING COMPARISON POINTS*

Another technique to record data on a part, with probing measuring devices, is using comparison points (also called surface points). This technique is very common as it provides information at any location on the part. The measuring device usually needs to be aligned on the part in order to record comparison points; otherwise, the deviations with respect to the CAD model cannot be calculated. Unlike when probing geometric features, the direction of compensation is dictated by the closest surface of the CAD model. Two different types of surface points, with different purposes, can be used using metrology software, namely the guided and unguided points.

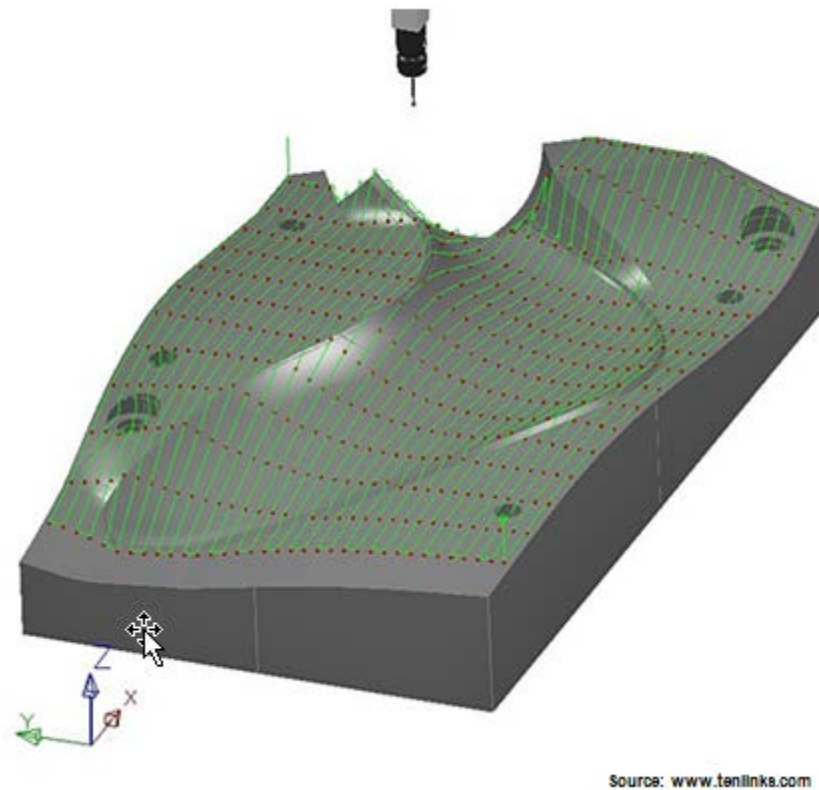


Figure 29: Representation of probed comparison points on a complex surface.

The unguided points are often called *points on the fly*; they are generally used to take points on the surface of a part at any location. This type of comparison point is used when a lot of points need to be recorded and the exact location of the point on the surface is unknown or unnecessary. Surface profiles are usually computed using this kind of comparison point.

The guided surface points must be recorded at a specific location on the surface of a part. Since there is no visual reference on the real part to indicate where to record the point, the virtual probe available in the 3D scene of the metrology software is used to guide the user towards the proper location before recording the point. Therefore, the software does not allow the user to record the point as long as the probe has not moved from within the acceptable tolerance zone. Once again, the measuring machine must be aligned on the part; otherwise, the location of the virtual probe with respect to the CAD surface will not be helpful. This type of comparison point is often used to perform alignments using datum targets.



Surface or comparison points can also be used to perform different types of alignments. The information usually of interest, when using comparison points, is the 3D deviation of each point compared with the CAD model. These points are often used to compute complex GD&Ts, especially the calculation of surface profile.

### *2.7.3. POSITIONINGS OF ELEMENTS*

Instead of being used to measure an existing physical object, the measuring devices are often used to place elements that are part of an assembly or that will be welded on a part at precise positions and orientations. This technique is widely used in the industry and is typical of applications that can only be done with portable CMMs. This process sometimes requires the CAD model of the final product, which is loaded in the metrology software to act as a reference object.

The first step is to perform an alignment on the basis upon which the components are fixed. Using a CAD model, or not, in the inspection program will lead to different alignment techniques. Once again, if a 3D CAD model is used, performing an alignment will express the measurement data in the CAD coordinate system.

For inspections without CAD models, a new coordinate system is created by the alignment. In this case, the inspector has to make choices regarding how he or she wants to express the data so that it will be useful to position the other parts. For instance, it is often useful to define the longest dimension of a part as the x-direction, define the x-y plane with the largest planar surface of the part, and place the origin at the center of a hole. Once an alignment is performed, the user can simply bring the part to be positioned over the base and with the probe in contact with one of its surfaces. Usually, one direction is adjusted at a time. Then, the orientation is verified, and so on. Depending on the required level of accuracy, this process can be iterative and may require extra tooling to position and properly orient the part. Care must be taken to take into account the diameter of the probe.

Inspections using CAD models are convenient, because it is possible to have information regarding the 3D deviation (compared to the CAD model) of each surface, instead of using only orthogonal directions. In all metrology software, the digital readout available is always



used to perform these kinds of operations; this readout enables the user to directly view the Cartesian coordinates instead of having to record points at each position.

Another similar application of measuring devices is to use a point probe to mark the part at specific and precise locations. The device must be aligned on the part before undertaking this process. This technique is also very common as it allows an intervention at a mid-stage of the manufacturing of a part. It is useful, for instance, to locate holes that need to be drilled on a part with respect to the global shape of the part that has already been manufactured. In this case, a “best-fit” alignment will be performed using comparison points on the entire surface before starting to mark the part with the point probe.

#### *2.7.4. SCANNING THE PART*

Scanning a part usually does not require performing an alignment to record the measurement data. Unlike probing technologies, it is possible to measure points all over the surface without being aligned on the part. Therefore, the data is directly acquired in the device coordinate system. The terms of use of the scanner must be followed carefully to optimize the quality of the scan.

Typical directives regarding the terms of use of 3D scanners are related with the chosen resolution, type of surface, scanning speed (sweeping of the scanner over the surface), and distance to the scanned surface. Moreover, depending on the surface of the part and the scanning technology used, the part might have to be powdered to ensure that the reflective properties of the surface are adequate for the scanner.

3D scanners allow measuring a very high amount of data in a very effective way. Creaform’s MetraSCAN 3D is a very good alternative as it includes all the same benefits and technology of the HandyPROBE while offering the same volumetric accuracy.

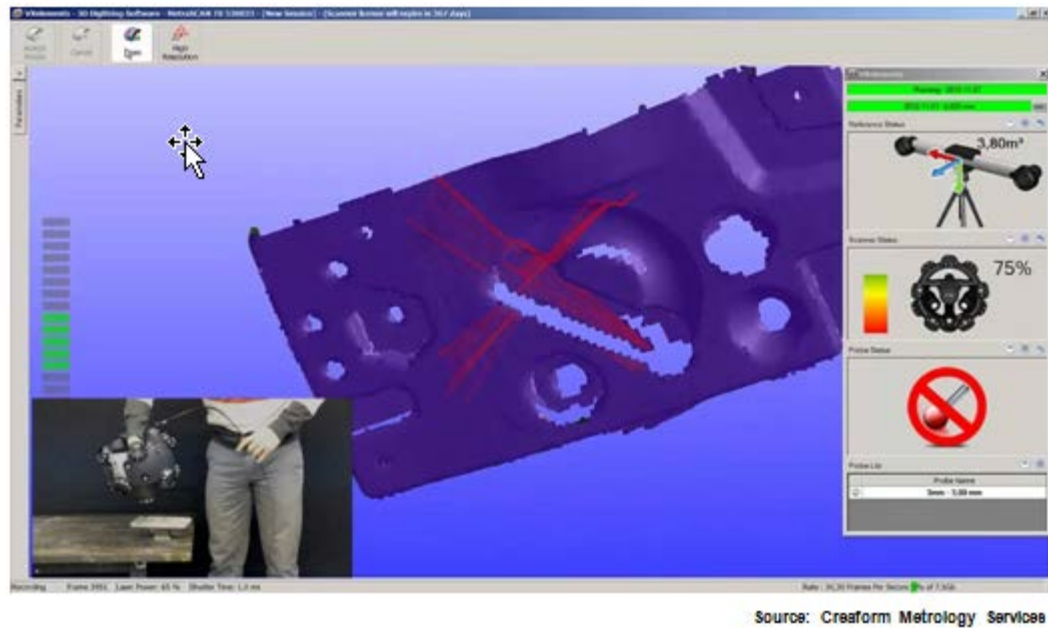


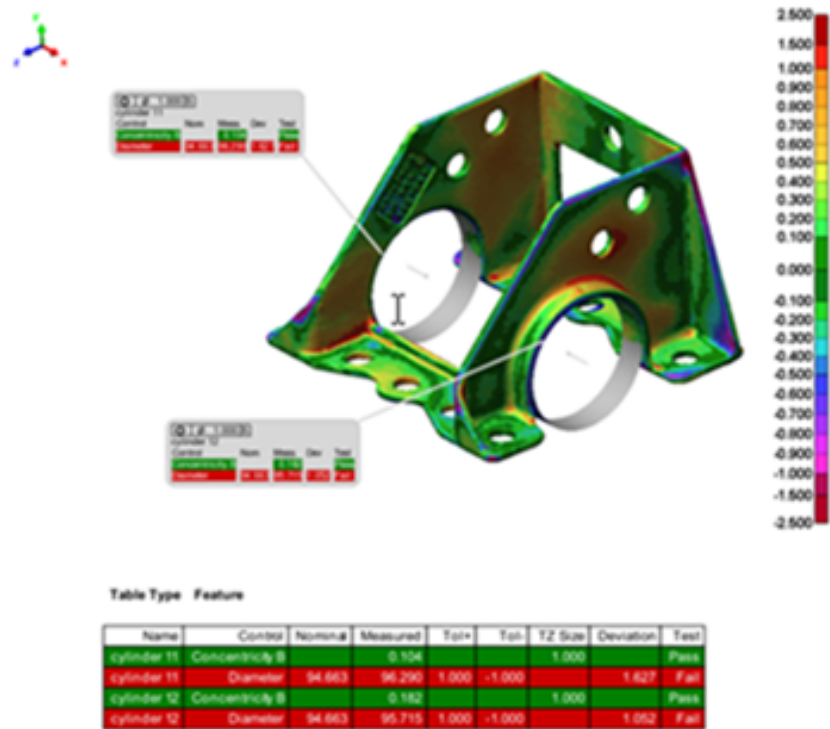
Figure 30: Object being scanned by the MetraSCAN.

## 2.8.EXTRACT RELEVANT INFORMATION AND GENERATE REPORTS

This stage of the workflow is, most of the time, completed when the inspection program is built. Indeed, calculations with the measurements can be automated—even before measuring the part. Once the data is recorded, everything is computed automatically. However, depending on the metrology software used, it is possible that some calculations cannot be automated. This is the case if the deviations of comparison points must be reported in a table using the alignment computed by a surface profile GD&T. The main purpose of this step is to extract the relevant information from the measurements and format it so that it can be reported according to the customer's needs. It is always recommended to organize the inspection program by keeping in mind how the data is going to be reported. Renaming the elements in the inspection program according to a bubbled drawing usually helps to organize the program's entire structure.

# FEATURES INSPECTION AND GD&T

## Central Openings Concentricity



Source: Creaform Metrology Services

Figure 31: Example of an inspection report.

With scanning technologies, most of the manipulations of the information extraction and computations occur after inspecting the part. Unlike probing technologies, geometric features are not created at the same time as the measurement data is recorded. Therefore, the geometric features need to be extracted from the data afterwards. It is preferable to have a human in the loop to perform this operation, even if automatic extraction features are available in some software. The reason: the efficiency of these tools relies completely on the quality of the raw data, which only a human can ensure.

The type of information extracted from the measurement data can vary a lot. In fact, any element of a physical object that is related with geometric dimensioning and tolerancing can be of interest. More specifically, these elements can vary from simple size dimensions to 3D deviations of surface points to more complex GD&Ts. There are four main categories of GD&Ts that control completely different things of a part feature: its form, orientation, location, and surface profile.

Once all the relevant information is extracted from the measurement data and properly organized in the inspection program, a report can be generated and exported to show the results in an effective way. Typically, an inspection report includes tables of features and comparison points that show tolerances and deviations. They also feature snapshots so as to locate the elements of the tables on the part. Most metrology software includes such useful tools to generate reports in a very effective way.

## CONCLUSION

As part of a comprehensive continuous improvement process, QC has become almost mandatory for any industry. Indeed, rejecting defected parts in a production line, monitoring the inherent quality of the product, or even increasing the quality of production tools are fundamental ways to improve a company's manufacturing process as a whole.

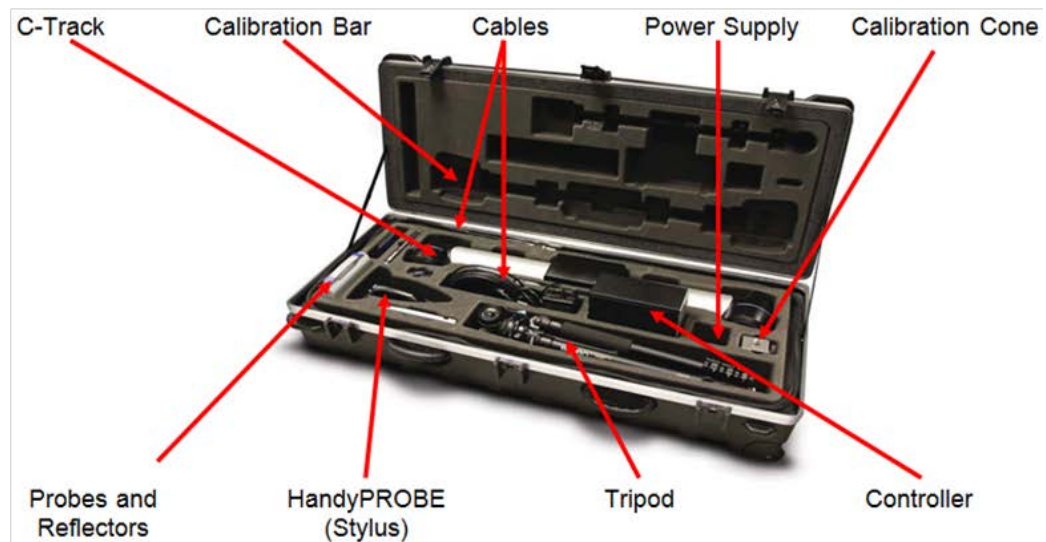
Over the past years, metrology companies have developed several methods and devices for this purpose. From manual tools, such as calipers, to portable optical CMMs (such as Creaform's HandyPROBE, measuring devices have evolved, bringing new possibilities in terms of QC.

Portable optical devices have brought a new dimension in 3D inspection. They allow the user to bring the measurement device to the part—instead of bringing the part to the device—with a maintained accuracy. Measurements can be conducted in workshops and on production lines. What's more: they do not depend on measuring conditions. This breakthrough improvement, compared with classical CMMs that are often more accurate but impossible to move, makes the QC process quicker and simpler.

The probing devices described in this teaching manual are all contact measurement tools. Another technology, the 3D scanning devices, can also provide accurate measurements for surface inspection. Instead of measuring points, these devices can quickly acquire an entire part of the surface of an object. As 3D scanners represent a quicker way to control the global shape of an object or the profile of a surface, the combination of the most modern optical-touch probing and scanning tools is certainly a good way to cover all the needs in dimensional control.

### 3. HANDYPROBE LAB GUIDE

#### 3.1.OVERVIEW AND SYSTEM DESCRIPTION



Source: Creaform Metrology Services

Figure 32: HandyPROBE System Hardware

The Creaform HandyPROBE is an arm-free portable coordinate measuring machine (CMM) that generates high-accuracy measurements. The device features three wireless communication buttons with the software and the *Controller*, providing good freedom of movement during measurements.

The following figure summarizes the button functions of the **HandyPROBE**, as well as the meaning of the different sounds emitted by the device.

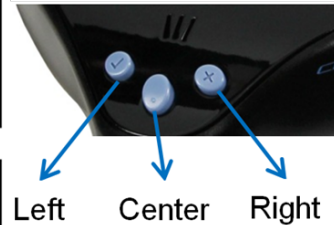
BUTTONS	FUNCTION
Left	Validating the measurement
Center	Acquiring a dot
Right	Cancelling a dot
3 buttons simultaneously (hold for 5 seconds)	Reboot
Left and right simultaneously	Associating with the controller

SOUNDS	MEANING
Short Sound	Acquisition validated
Long sound	Acquisition failed
2 or more sounds	Multipoint acquisition
Low intensity	Batteries lower than 60%

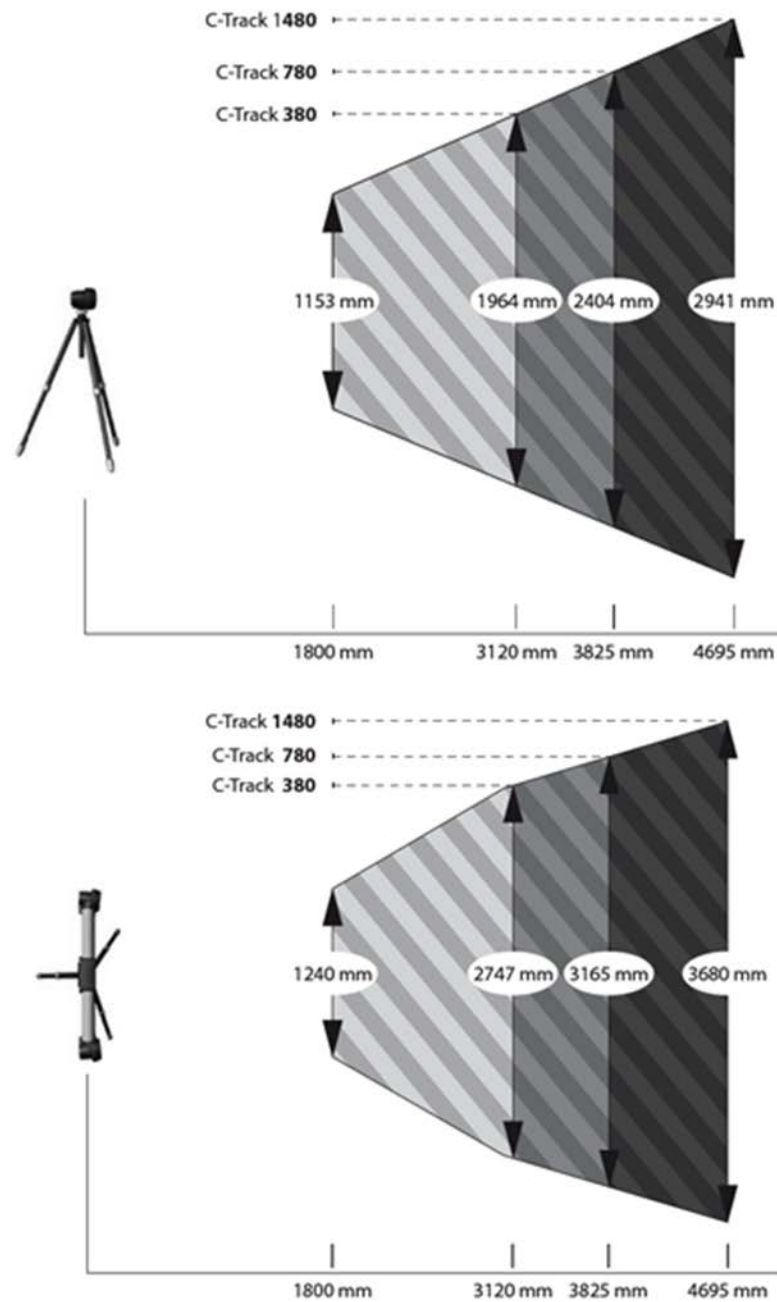
**NOTE:** The HandyPROBE requires two AA batteries.



Source: Creaform Metrology Services

Figure 33: HandyPROBE button functions and sound meaning

The HandyPROBE is fitted with the C-Track dual camera sensors, enabling the device to measure reflectors within the operating space. Therefore, the C-Track can be considered “the eyes” of the system, since it live tracks the HandyPROBE 30 times per second. In addition, the C-Track provides the exact localization of the HandyPROBE using triangulation, performs continuous image acquisition and transmission, ensures that the reflectors are lit and manages the interfacing with the computer and the storage of the sensor parameters. The C-Track also has an internal sensor that compensates measurements for temperature changes. Creaform offers 3 C-Track models: the 380, 780 and 1480. The number, usually following the “C-Track” name, refers to the measurement volume: 3.80m<sup>3</sup> for the 380, 7.80m<sup>3</sup> for the 780, and 14.80m<sup>3</sup> for the 1480. A figures representing the difference between the three C-Track models and their respective measurement volume is shown below:



Source: Creaform Metrology Services

Figure 34: Creaform C-Tracks measurement volumes

The optical reflectors are made of the same material as the HandyPROBE. The system includes swivel reflectors (figure 31) and stickers that can be directly secured on the parts to be measured. Reflectors are fragile so they should be handled with care and not touched if at all possible: the C-Track does not recognize damaged reflectors. The reflectors are used to



create a dynamic referential, the key factor for a system that eliminates the impact of environmental conditions (such as vibrations) on the measurements. In fact, a part could be inspected while held in someone's hands without losing any accuracy, as long as the reflectors are rigidly secured on it.

The calibration bar, used to calibrate the C-Track, is made of carbon fiber and reflective targets. It consists of a traceable certified artefact and is the only part of the system requiring annual recertification. The calibration cone is used to calibrate the HandyPROBE stylus.

The controller is considered “the brain” of the system, as it communicates with the C-Track, the laptop and the HandyPROBE while processing the images taken with the C-Track. The controller provides a status for all systems available with the green LEDs and presents information on C-Track, probe, scanner, reset servers and options through 5 different menus. Moreover, it enables the user to perform actions such as associate probe, set language/contrast and reinitialize controller. The communication between the controller and the computer is done through the Ethernet protocol and can be set up using the IP configuration tool.

The system includes several probes of different lengths and diameters including quick connect adapters, making it possible to swap from one probe to another without having to recalibrate.

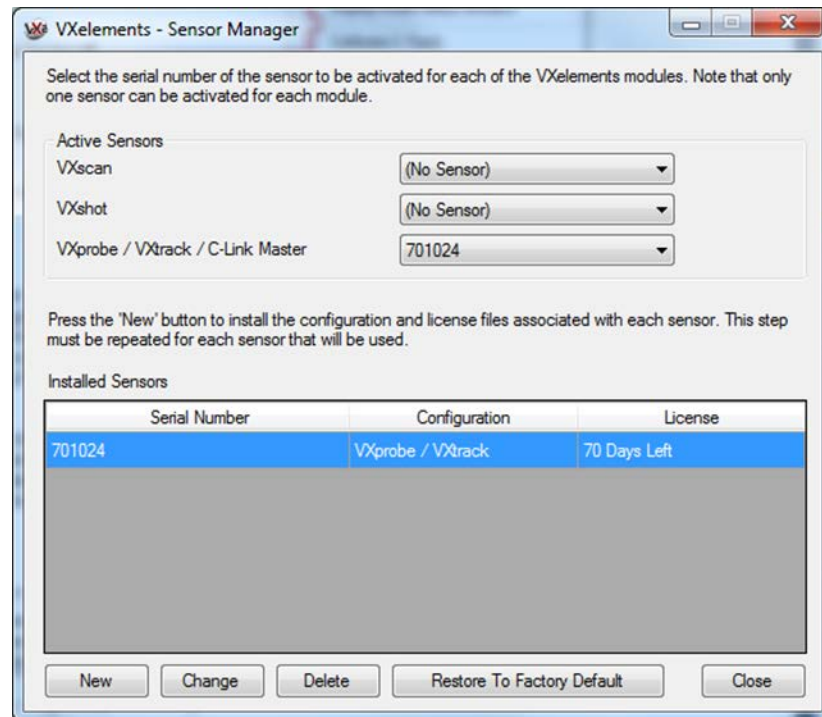
## 3.2.SOFTWARE INSTALLATION, DEVICE LICENSE MANAGEMENT AND CONFIGURATION FILES

### 3.2.1. *INSTALLING VXELEMENTS*

VXelements is a fully-integrated 3D data acquisition software program for performing simultaneous measuring data acquisition using Creaform equipment and reflectors. The software can be installed from the CD-ROM provided by Creaform or from the support section of Creaform website. To ensure that you have the latest version of VXelements and the required CD-Key on hand, please refer to your secured account on the Creaform Support website for software updates. Providing that your computer has the minimum requirements to operate the software, follow the instructions to complete the installation.

### 3.2.2. LICENSE AND CONFIGURATION FILES

Once VXelements is installed and the license (.clf) and configuration files (.cst) are retrieved from the Creaform support website, files must be loaded into VXelements. This operation is done by opening the files through the Sensor Manager (directly by clicking on files), or by opening the Sensor Manager from the Windows Start Menu.

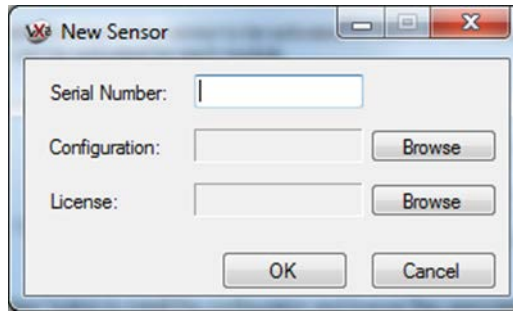


Source: Creaform Metrology Services

Figure 35: VXelements Sensor Manager

The Sensor Manager will display a warning if the license you are trying to install is more restrictive than the previous one (shorter validity, etc.). The license and calibration files are specific to the VXelements version used. Therefore, when downloading a new version of VXelements, new license and configuration files are needed as well.

Click on NEW or CHANGE button to associate or update the license and configuration files for the desired products, and the following window will be displayed.



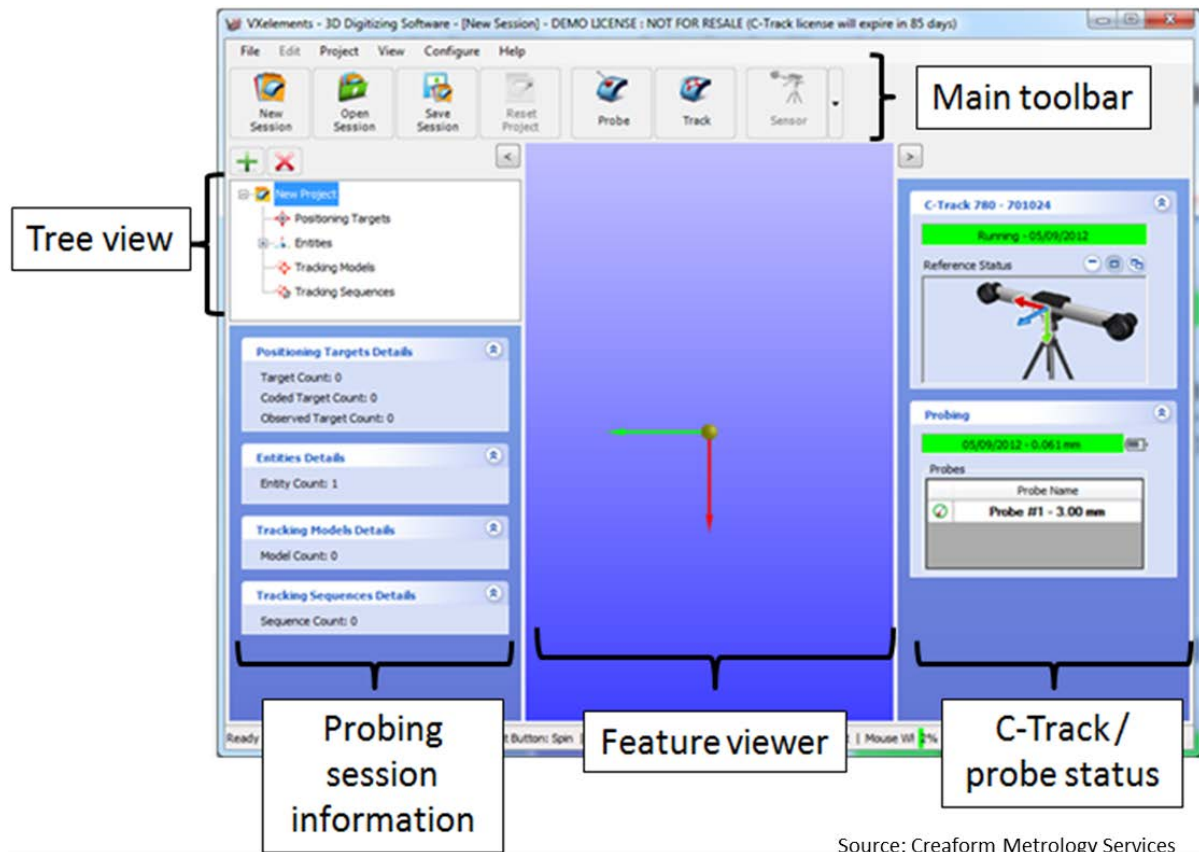
Source: Creaform Metrology Services

Figure 36: Selecting a new sensor within Sensor Manager

Then browse to your download folder to find the configuration file (.cst) and the license file (.clf). Once associated, both license and configuration files can be moved or deleted without affecting VXelements.

### 3.3.VXELEMENTS USER INTERFACE

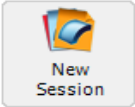
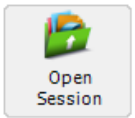


The VXelements software is used to create and manage a target dynamic referential, as well as to acquire measurement data with the HandyPROBE, the MetraSCAN 3D or the MaxSHOT 3D. Entities can be created and probed in VXelements, and new coordinate systems can be created to express the measurement data. The software includes different wizards to perform the calibration of the measuring devices. Moreover, it is designed to provide visual feedback to the user while inspecting a part, mostly regarding the different system and detection statuses. VXelements includes powerful algorithms that run in the background to filter and treat the measurement data in real-time, in order to optimize measurement accuracy for both scanning and probing technologies. The following figure presents a snapshot of the VXelements user interface.

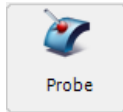


Source: Creaform Metrology Services

Figure 37: VXelements user interface

The following table describes the main buttons of the VXelements Main Toolbar:

	To create a new session file.
	To open an existing session file.
	To save the current VXelements session file.
	To reset the current project. The project parameters will not be reinitialized in New Session.



To start and stop probing.



To add a new project to the session.



To remove the current project from the project tree.

Table 4: Main buttons available in the VXelements main toolbar

### 3.3.1. SYSTEM INFORMATION

The right pane contains information on both the C-Track and the HandyPROBE, as shown in the following figure.

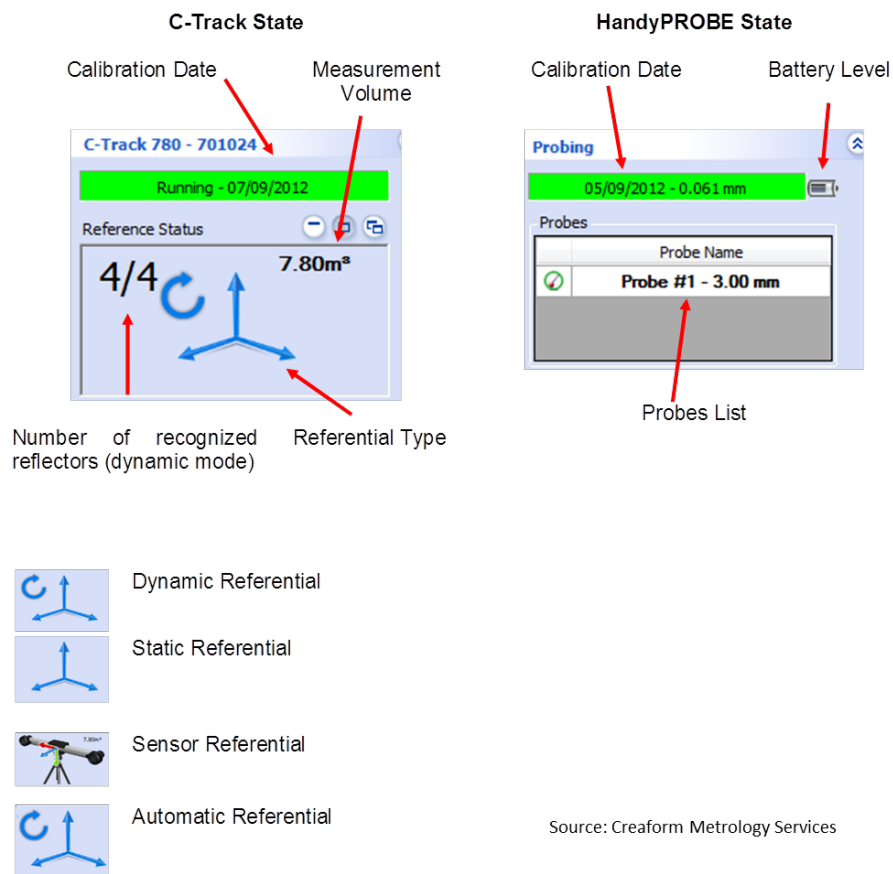
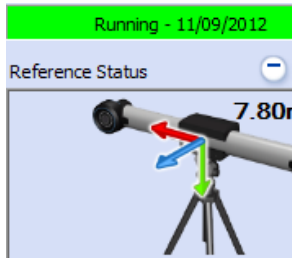


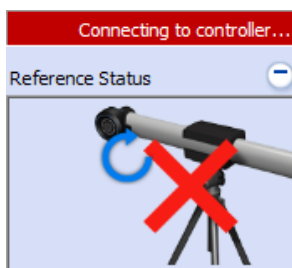
Figure 38: Information available in VXelements - C-Track and HandyPROBE state

### 3.3.2. C-TRACK STATUSES

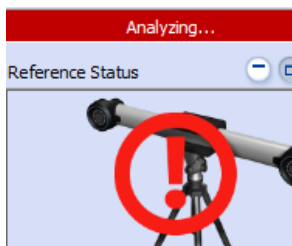
The following table summarizes the statuses of the C-Track:



The C-Track is connected, initialized, and ready to use.



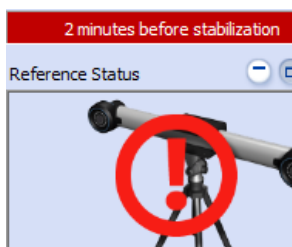
The controller is being initialized.



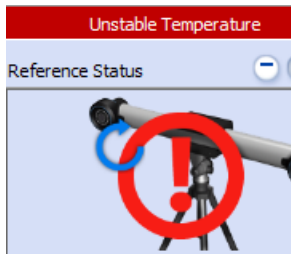
The software is analyzing the C-Track status, in order to verify if the temperature is stable. This operation can take several minutes.



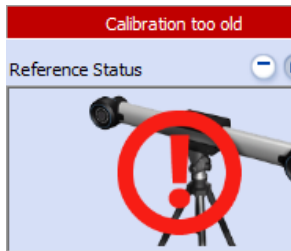
The C-Track is warming up.



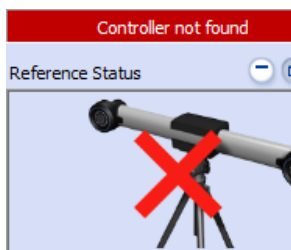
The C-Track is warming up, and the remaining time is approximately two minutes.



The C-Track has detected a temperature variation and is currently analyzing whether the calibration is valid.

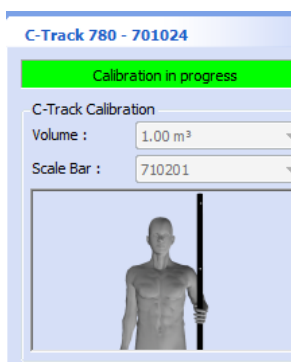


The C-Track needs to be calibrated again.



No controller has been detected.

Probable causes: wires and cables are not properly connected, IP address is incorrect in IP Configurator, etc.

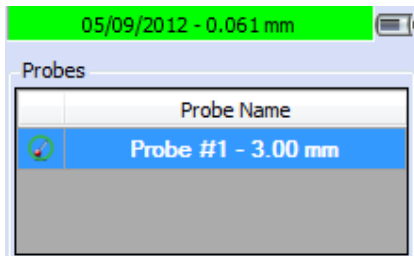


The C-Track is being calibrated.

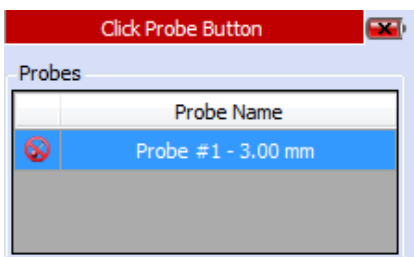
Table 5: List of C-Track statuses

### 3.3.3. HANDYPROBE STATUSES

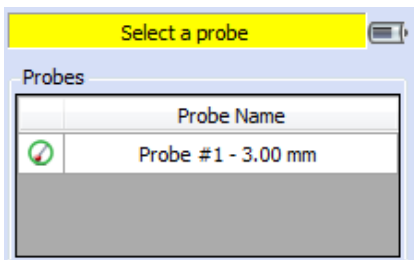
The following table summarizes the different statuses of the HandyPROBE.



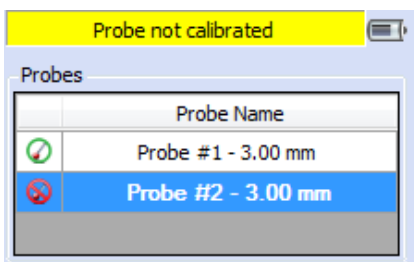
The selected probe is calibrated and ready to use.



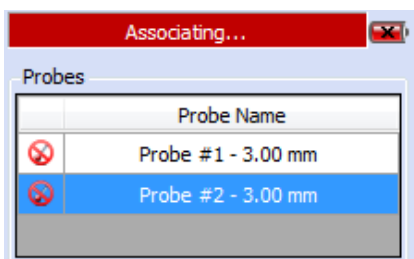
Press a button on the stylus to activate communication between the controller and the stylus.



Select or create a probe.



The selected probe is not calibrated.



An association between the HandyPROBE and the controller must be performed for the first use or for hardware reinitializing.

Table 6: List of the HandyPROBE statuses



### 3.3.4. DETECTION STATUSES

The following table summarizes the different detection statuses of the HandyPROBE and the dynamic referential.




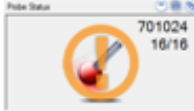


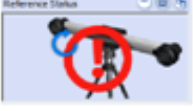

DYNAMIC REFERENTIAL		HANDYPROBE	
	Sensor Referential		No stylus detected
	OK		OK
	Not detected		Not detected by the C-Track
	Outside of the calibrated volume		Outside of the calibrated volume
	Outside of volume		Outside of volume
	Unstable temperature		Unstable temperature
	Too much light (sun, object directly in front of the camera, etc.)		

Table 7: HandyPROBE and dynamic referential detection statuses

### 3.4.VXPROBE USER INTERFACE

The VXprobe module enables using the HandyPROBE within metrology software, and all the VXelements functionalities are available through this interface. VXprobe is compatible with the following metrology software:

- ▶ BuildIT Software & Solutions (BuildIT)
- ▶ Delcam (PowerINSPECT)
- ▶ Geomagic (Studio and Qualify)
- ▶ Innovmetric (Polyworks Inspector)
- ▶ Inspect 3D (Inca 3D)
- ▶ Metrologic (Metrolog)
- ▶ New River Kinematic (SpatialAnalyzer)
- ▶ Rapidform (XOR and XOY)
- ▶ Verisurf (VerisurfMeasure)
- ▶ Wenzel Metromec (Metrosoft CM)

#### 3.4.1. *LAUNCHING THE VXPROBE INTERFACE*

To use the VXprobe interface, launch the metrology software and plug in the HandyPROBE with the software connection tool. The VXprobe interface will appear at this time.

#### 3.4.2. *USING THE VXPROBE INTERFACE*

The VXprobe interface is a window that includes the following elements:

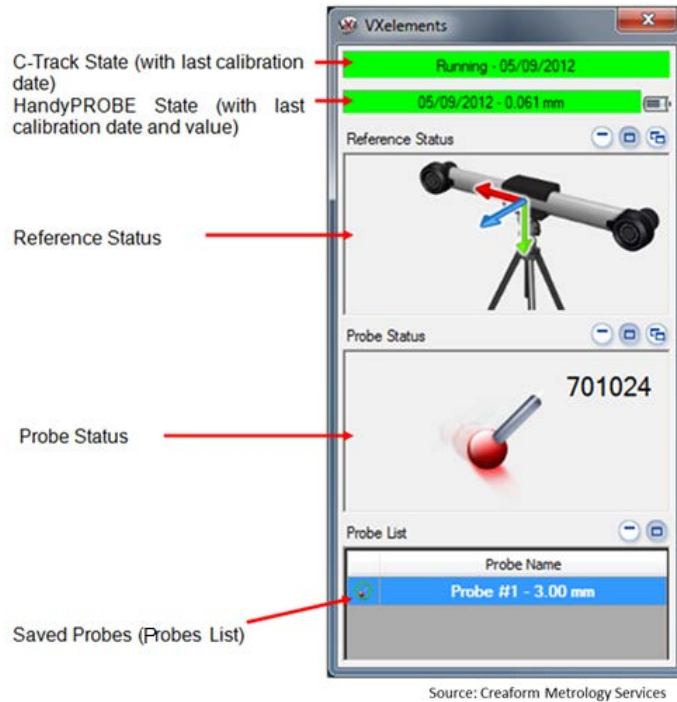


Figure 39: VXprobe interface

The following menu can be accessed by right clicking on the interface window:

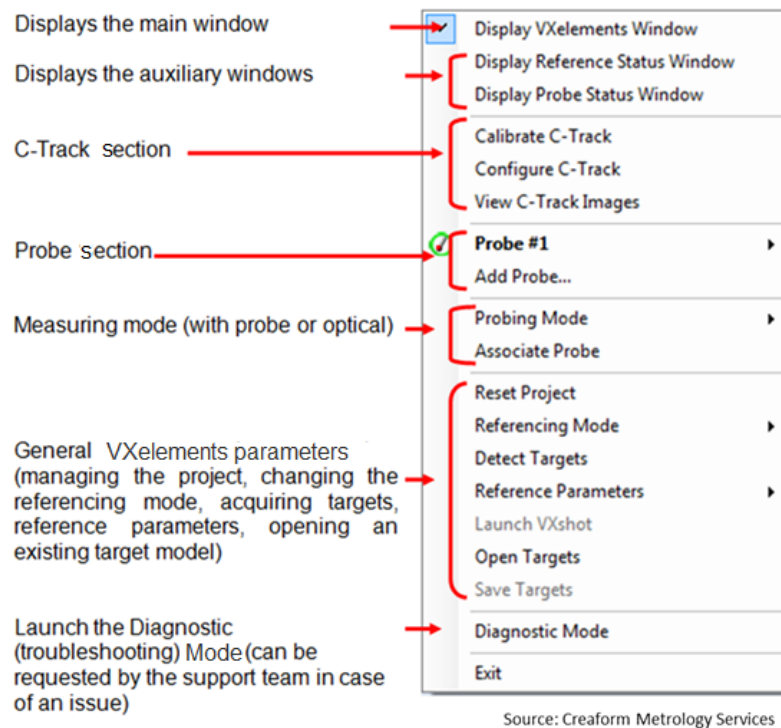
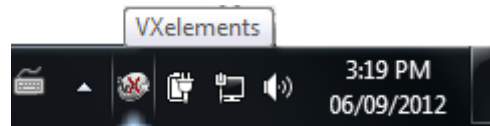


Figure 40: VXprobe dropdown menu

### Tips & Tricks

If the VXprobe interface is not displayed, the icon can still be found in the Windows notification zone. Clicking on this icon, the VXprobe window is displayed again.



## 3.5.TYPICAL INSPECTION WORKFLOW WITH THE HANDYPROBE

Once VXelements is properly installed properly and the device license and configuration files are correctly added with the Sensor Manager, the inspection process can start.

The following table summarizes the main steps of the typical workflow for performing an inspection with the HandyPROBE:

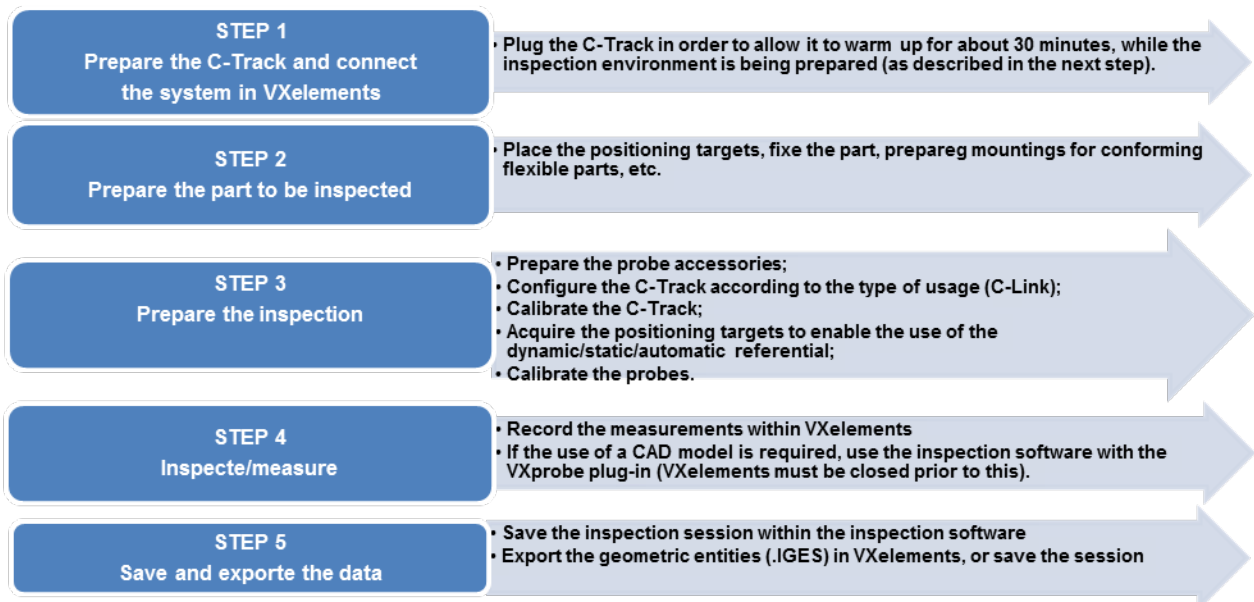
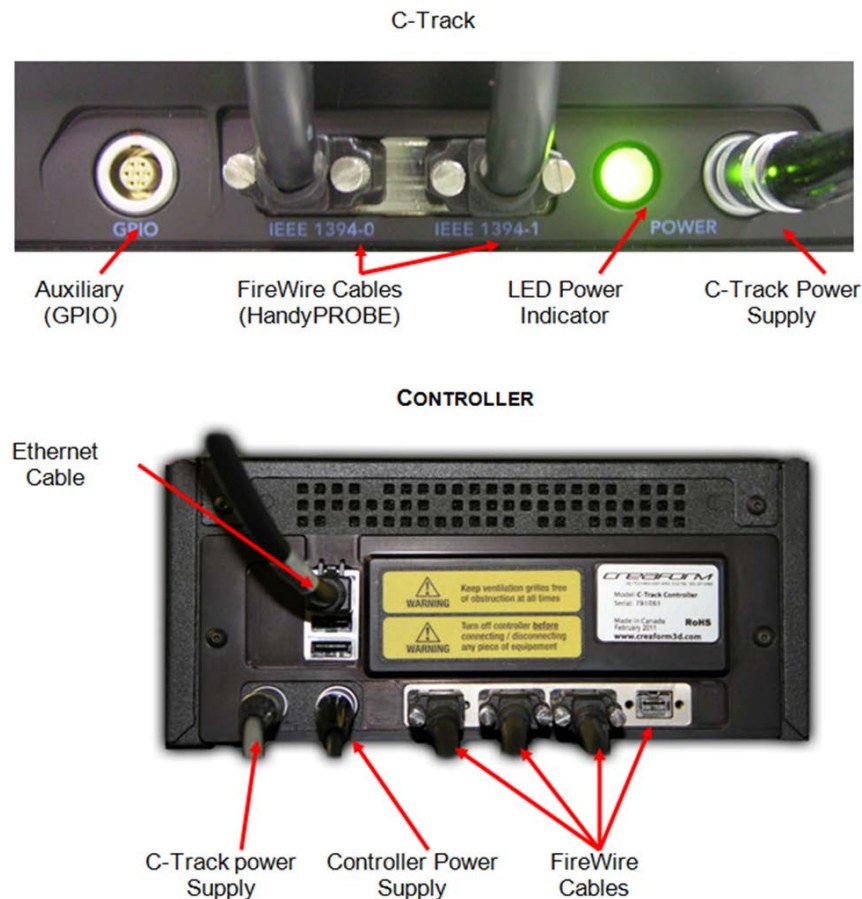


Table 8: Typical inspection workflow using the HandyPROBE

### 3.5.1. PREPARING THE C-TRACK

The first step of the workflow is to connect the system. This way, the C-Track can warm while other tasks are performed. Before installing the C-Track on the tripod, make sure that the tripod is screwed up tight. The following steps should be followed to establish connections properly:

1. Plug the FireWire and power supply cables in the C-Track;
2. Plug the other side of the FireWire and power supply cables in the controller;
3. Plug the Ethernet cable with the USB adapter in the computer;
4. Plug the power cord from the controller to the power source;
5. Power on the controller (make sure everything else is plugged in before starting the controller).

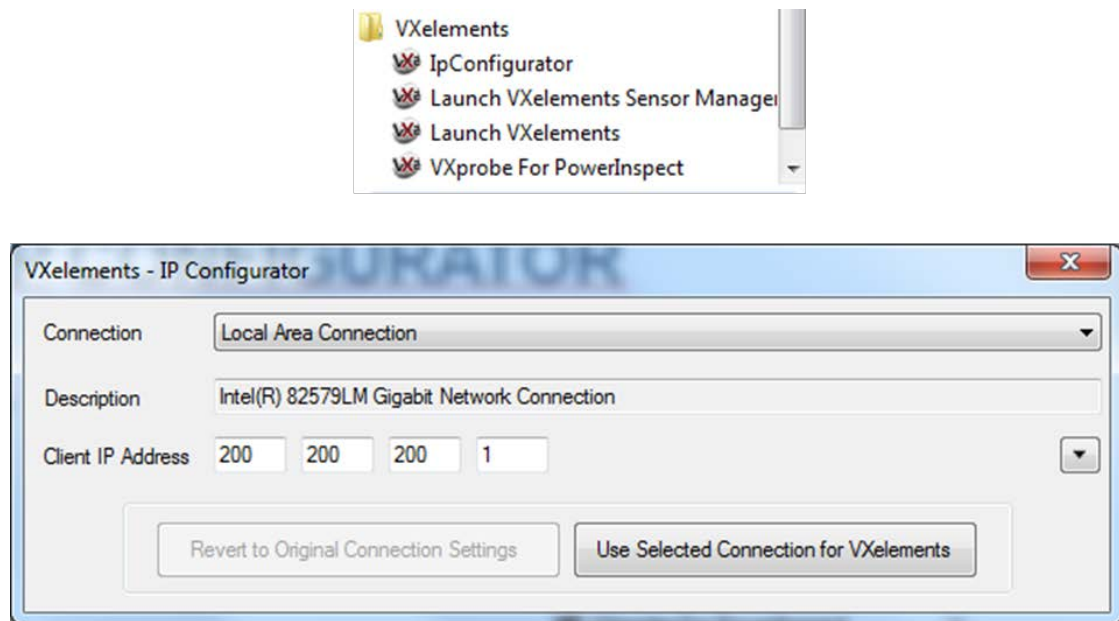


Source: Creaform Metrology Services

Figure 41: HandyPROBE system connections

Wait for the system to warm up and have its temperature stabilized in the environment: the controller displays “Ready” once the warming period is over. To disconnect the system, the steps from the previous section should be performed in the opposite order. Make sure to shut down the controller before disconnecting the rest. During set-up, make sure that no light is directly pointing at the cameras.

Once all the hardware connections are established and the controller is powered on, the system can be connected in VXelements. First, launch the VXelements *IP Configurator* from the start menu, and click on the “Use Selected Connection for VXelements” button. The IP Configurator tool must be launched each time the USB adapter is plugged in a new USB port. The IP address of the network card can also be set manually (to 200.200.200.1) if the USB adapter is not used.



Source: Creaform Metrology Services

Figure 42: The VXelements IP configuration tool (IP Configurator)

This window can now be closed and VXelements can be opened to view the state of the system (which should be “warming” at this point).

### *3.5.2. PREPARING THE PART TO BE INSPECTED*

The Creaform HandyPROBE features one significant conceptual difference with other portable inspection devices: the part to be inspected does not have to form a rigid body with the measuring machine. This is due to the fact that the C-Track constantly and simultaneously observes both the HandyPROBE and a dynamic referential that is rigidly fixed on the part. The dynamic referential is built using several optical reflectors that are secured on the part. The following rules must be understood and followed by the user when creating a dynamic referential:

1. There must be enough targets. The system needs a minimum of 3 targets to work; however, the number of targets should be higher in a good setup (6 to 12 depending on the size of the part).
2. Distribute the targets within the volume (targets should cover the space in three orthogonal directions). Positioning targets should not be aligned.
3. The reflectors should encompass the location where the measurements are taken as much as possible. In other words, place the positioning targets all around the part (above, under, right, left, in front, behind).
4. The positioning targets have to face the C-Track as much as possible. Angles up to 45 degrees are tolerated; for angles wider than that, acquiring the targets will not be automatic.
5. Make sure to use clean and undamaged targets.



Source: Creaform Metrology Services

Figure 43: Example of damaged reflectors

### ***Tips & Tricks***

- ▶ Make sure to have a clean surface to apply the targets on. If they are applied on a greasy surface, the targets might fall.
- ▶ Make sure to apply the targets in order to create a **single** rigid body. Indeed, no relative movement is allowed between the targets that are part of the same referential. For instance, if a dynamic referential must be created on an entire car, don't put targets on the wheels as they are not rigid with the body of the car (because of the suspension).
- ▶ Fix your targets on the part using glue tape, etc. Targets can easily move if they are not fixed properly.
- ▶ Make sure the swivel targets sit completely on their base. Be careful when rotating them that they remain in contact with the bases.
- ▶ Take into account that you might hide some of the targets during the inspection.

The optical reflectors can either be secured directly on the part to be inspected or on a rigid inspection table where the part is going to be secured. The main idea is that the targets must form a rigid body with the part. If the targets are secured directly on the part, the part does not have to be fixed in space. On the other hand, if the targets are placed on an inspection table, the part must also be fixed on the table during inspection. The main



challenge of setting up of the part with the targets resides in finding a solution between securing the targets with the part while keeping all elements to measure accessible, and ensuring that as many targets as possible are visible while taking the measurements.

When you work with a part bigger than the the C-Track measurement volume, you might want to extend your volume by moving the C-Track (for instance when a MaxSHOT 3D is not available). In this case, the key is to start in the middle of the volume and then gradually move the C-Track using small steps and a good overlapping to acquire other targets.

### 3.5.3. PREPARING THE INSPECTION

#### 3.5.3.1. PREPARING THE PROBE ACCESSORIES

The HandyPROBE is able to manage all probe diameters, as long as they have been properly configured. The desired probing sphere need to be mounted on the HandyPROBE, and then pre-configured in VXelements. To configure a new probe, proceed as follows: **Configure > Probes > Add**

Give a **name** to the new probe profile, and enter the **diameter** in mm. This way, the software can keep a trace of the different probes used for measurements.



Figure 44: New probe configuration

#### **Tips & Tricks**

- ▶ The software is able to manage both straight and bended probes. You can choose the shape when creating a new type of probe.
- ▶ NOTE: once a new probe is configured, it still needs to be calibrated.

### 3.5.3.2. CHANGING THE C-TRACK CONFIGURATION ACCORDING TO THE USAGE TYPE (C-LINK)

The C-Track may need to be configured in order to be recognized by the computer. This is even truer when a C-Link system is used. The configuration consists in changing the IP address of the C-Track to avoid IP conflicts.

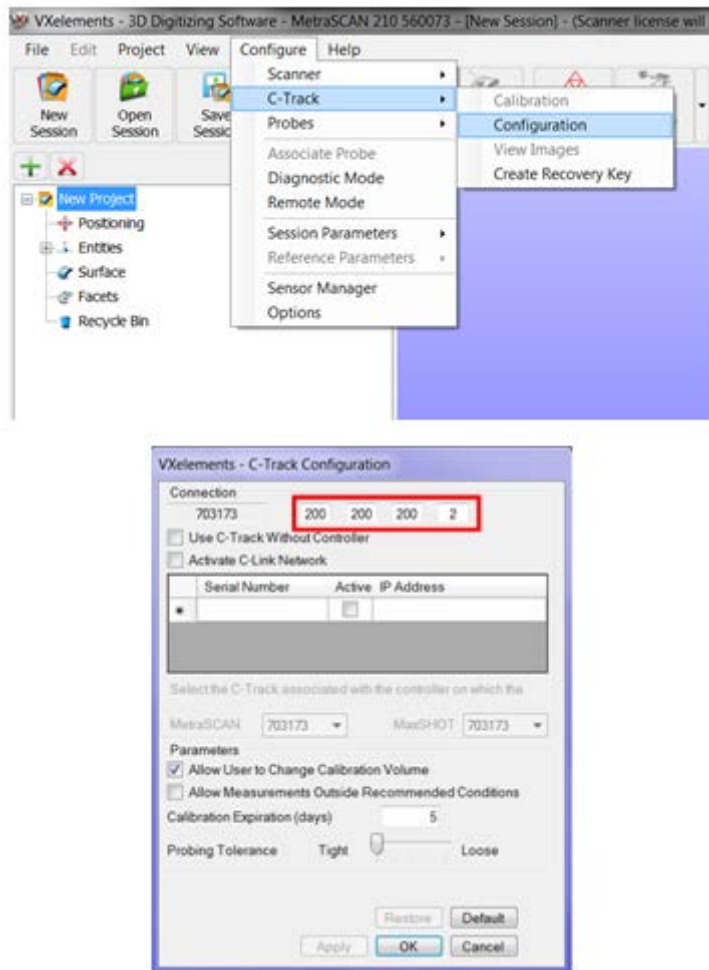


Figure 45: C-Track configuration – changing the IP address

### 3.5.3.3. CALIBRATING THE C-TRACK

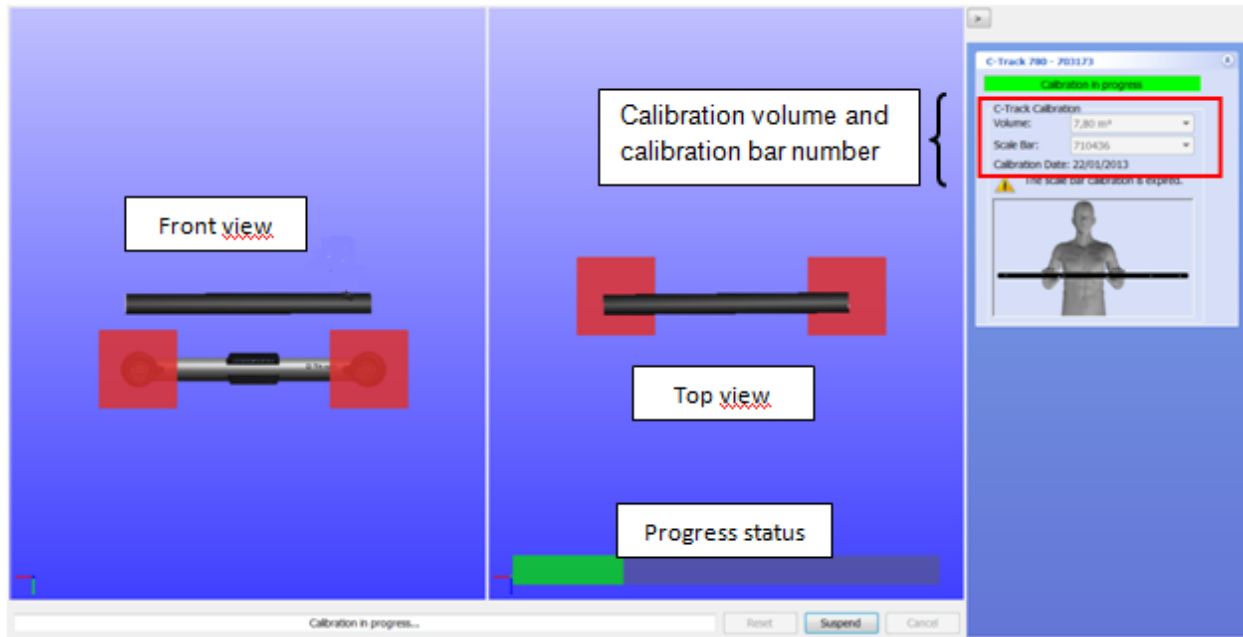


Figure 46: C-Track calibration

Only an optimized system guarantees accurate results during the measurement operations. The C-Track calibration is an optimization process made to ensure that the measurements will stay within the specifications values. This process is done through a VXELEMENTS wizard that guides the user while running algorithms in the background to reduce human error. The calibration procedure includes the following steps:

1. Enter the C-Track calibration interface: **Configure > C-Track > Configuration**;
2. Set the calibration volume and calibration bar serial number;
3. Start and follow the calibration procedure as shown on the screen: move the calibration bar in order to match the positions shown on screen.

### ***Tips & Tricks***

- ▶ Handle the scale bar carefully (very fragile).
- ▶ Do not touch the reflective positioning targets.
- ▶ During the calibration procedure, try to match the squares shown on the screen to put the calibration bar in the right position.
- ▶ Check the picture of the person on the right: it indicates how to hold the calibration bar. There are 4 different positions during the whole process.

#### ***3.5.3.4. ACQUIRING THE POSITIONING TARGETS IN ORDER TO ENABLE THE USE OF THE DYNAMIC/STATIC/AUTOMATIC REFERENTIAL***

Since you must perform an inspection within the same reference frame, you need to acquire the positions of the referential targets to create the reference system. The coordinates of the targets and their relative positions will be saved, enabling the user to move the C-Track without losing the referential. To create a dynamic referential, proceed as follows: ***Positioning > Detect targets***

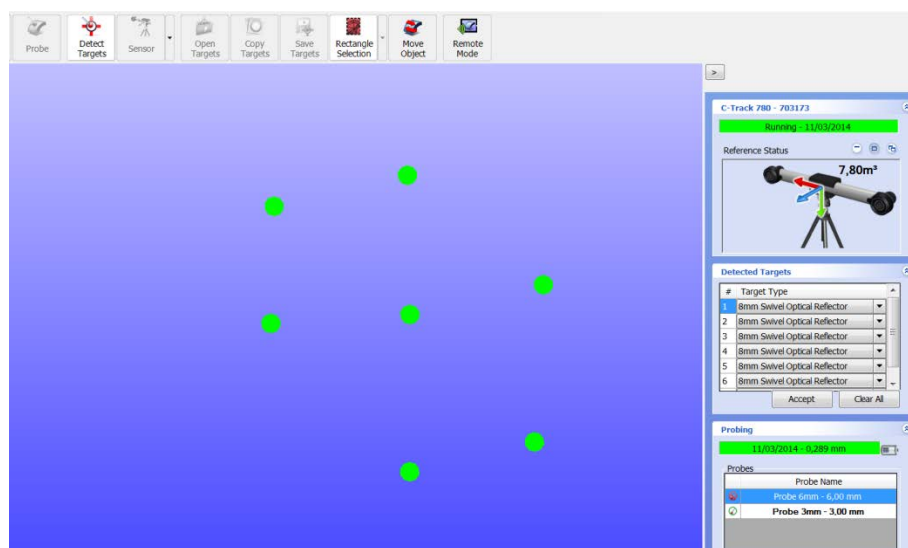


Figure 47: Targets detection

Select the desired targets to be added to the model: they will turn green on the screen once selected. To create the actual positioning model, click on **Accept button** on the right. The reference status is now on the top right corner of the screen.

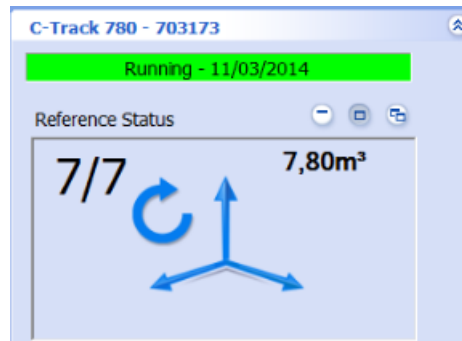


Figure 48: Reference status

#### 3.5.3.5. CALIBRATING THE PROBES

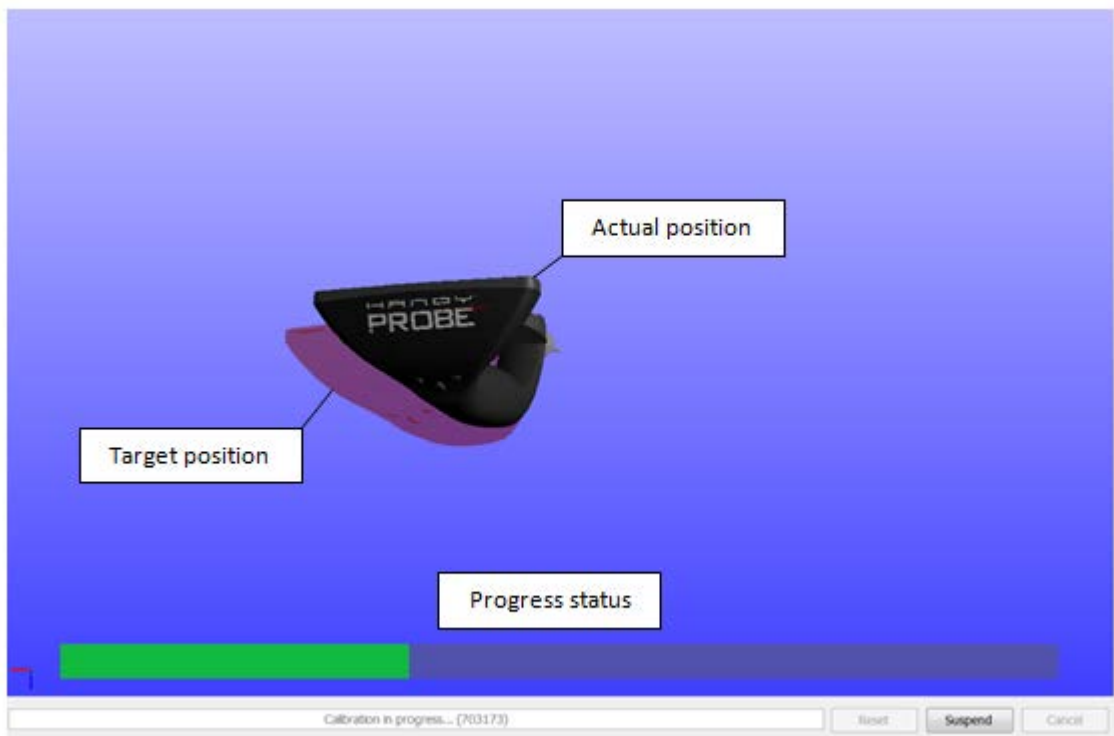


Figure 49: Cone artifact used for the C-Track calibration

Just like the C-Track, the probe needs to be calibrated to guarantee accurate results. The operation requires a cone artifact:

1. First start the calibration interface for the specific probe;
2. Put the probe in the cone and check the distance meter on the screen. Move the cone and the probe in order to position them at the right distance.
3. Follow the calibration procedure as shown on screen: rotate the probe in the cone in order to match the positions shown on screen.

#### ***Tips & Tricks***

- ▶ The calibration cone needs to be still and stable.
- ▶ Do not lose contact between the calibration cone and the probe ball during acquisition process.
- ▶ Optional: the results may sometimes be better if the calibration is done with a dynamic referential. To do so, the cone and the acquired targets need to be in the same rigid body.

#### 3.5.4. *INSPECTING/MEASURING*

NOTE: The following example illustrates how to acquire a plane. The procedure is similar for every other feature.

First activate the probing mode in VXelements, then go in the **Entities** menu and select the desired feature (here, a plane).

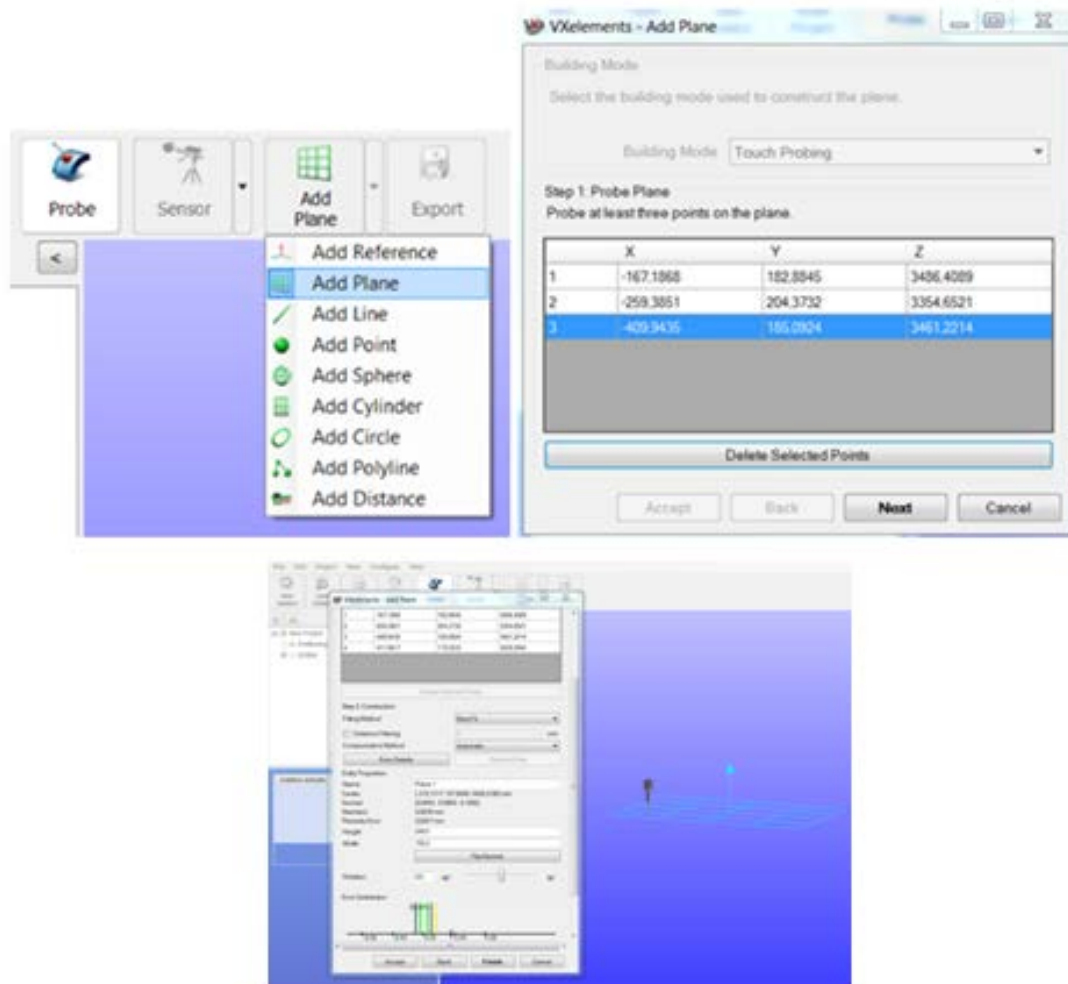


Figure 50: Adding a plane in VXelements

### Tips & Tricks

- ▶ Don't forget to activate the probing mode, or you won't be able to create any feature by probing points (only with existing ones).
- ▶ Probe the desired points with the *center button*, cancel the last taken point with the *right one* (cross) and validate the measurement with the *left one* (check).



### 3.5.5. SAVING AND EXPORTING THE DATA

#### 3.5.5.1. SAVING THE INSPECTION SESSION WITHIN THE INSPECTION SOFTWARE

The global inspection sessions can be saved as \*.csf files, a VXelements-specific format. The sessions will include all the information about positioning the targets model, alignment, calibration, parameters and probed data. To save a session, use the following path in the software: **File > Save session**

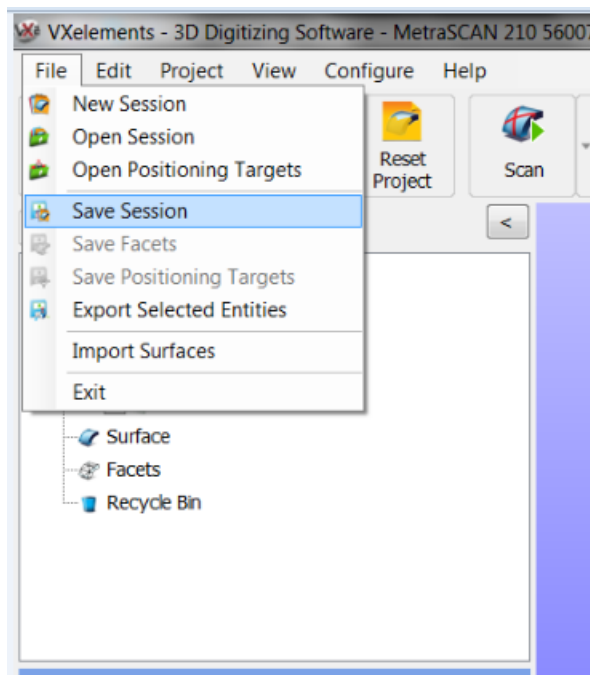


Figure 51: Saving a session in VXelements

### 3.5.5.2. EXPORTING THE GEOMETRIC ENTITIES (.IGES) IN VXELEMENTS, OR SAVING THE SESSION

Once all the desired features have been measured, an IGES file, including all the data, can be saved. This file will be workable in any other inspection software. First select the desired entities or click on entities in the tree to select all of them. Then use the following path: **File > Export selected entities**

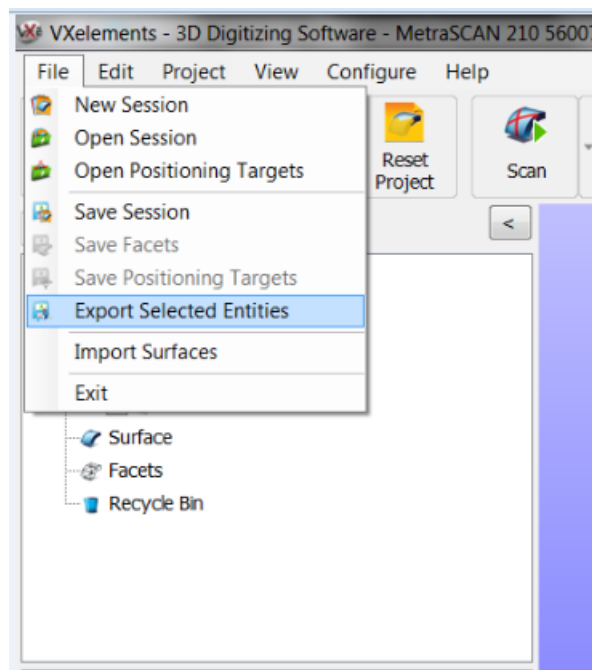


Figure 52: Exporting selected entities to an \*.iges file

#### ***Tips & Tricks***

- ▶ You can also right-click on the selected entities to export them.
- ▶ If you want to select and export only one type of entities, they can be sorted to ease the selection (***Entities > Right-click > Order entities > Sort by #***)

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