National Physical Laboratory

# Good Practice Guide No. 41

## CMM Measurement Strategies

David Flack

National Measurement System

Issue 2

# Measurement Good Practice Guide No. 41

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ABSTRACT
This guide covers the selection of the number of measurement points when using Co-ordinate Measuring Machines (CMMs) and gives advice on the compromise between accuracy and speed. It provides guidance on sampling criteria for standard features and advice on measurements that involve projections of features over long distances. It covers cleanliness, part loading/alignment and the effect of temperature, surface finish and geometry on the result. It also contains information on basic measurement principles, common measurement requirements, CMM software functionality in relation to drawing requirements and good metrology practice when using CMMs with CAD data to inspect parts.

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# Preface

The author hopes that after reading this Good Practice Guide you will be able to better understand CMM measurement strategies. The content is written at a simpler technical level than many of the standard textbooks so that a wider audience can understand it. I am not trying to replace a whole raft of good textbooks, operator's manuals, specifications and standards, rather present an overview of good practice and techniques.

## GOOD MEASUREMENT PRACTICE

NPL has defined six guiding principles of good measurement practice. They are:

1. **The right measurements:** *Measurements should only be made to satisfy agreed and well-specified requirements.*

2. **The right tools:** *Measurements should be made using equipment and methods that have been demonstrated to be fit for purpose.*

3. **The right people:** *Measurement staff should be competent, properly qualified and well informed.*

4. **Regular review:** *There should be both internal and independent assessment of the technical performance of all measurement facilities and procedures.*

5. **Demonstrable consistency:** *Measurements made in one location should be consistent with those made elsewhere.*

6. **The right procedures:** *Well-defined procedures consistent with national or international standards should be in place for all measurements.*

You can make a significant difference to your measurement capabilities by simply following these principles, which should all be part of your own quality system.

# Introduction

1

**IN THIS CHAPTER**

- What this guide is about and what it is not
- Introduction to measurement strategies and this guide
- General measurement strategy

This measurement good practice guide provides an overview of CMM measurement strategies. It is an update to a guide first published in 2001 and has been updated to reflect changes in the standards and improvements in technology over the last ten years.

## What this guide is about and what it is not

It is intended that this guide should give enough information so that the metrologist can make educated selections of the number of probing points and their distribution when measuring a component on a CMM. The guide also covers good practice regarding workpiece holding methods and part orientation. This good practice guide is not intended to be an authoritative guide to the standards and the primary reference should always be the standards themselves.

## Introduction to measurement strategies and this guide

### *Co-ordinate measuring machines*

Co-ordinate metrology has become essential for industrial dimensional metrology. Goods worth over £100M are inspected annually, in the UK alone by thousands of co-ordinate measuring machines. It is therefore essential that the accuracy can be estimated and traceability demonstrated. In addition, quality systems have brought about increased user awareness of the benefits provided by reliable and frequent checks of CMMs. Over the years, standards and guidelines have been developed to harmonize the performance specifications of a CMM to enable a user to make meaningful performance comparisons when purchasing a machine and, once purchased, to provide a well-defined way in which the specified performance can be reverified. For the user, demonstrating traceability to national standards and estimating the accuracy of measurements made with three-dimensional CMMs is of extreme importance for maintaining confidence and reliability in the measurements.

The ISO 10360 series of standards detail the acceptance, reverification tests and interim checks required to determine whether the CMM performs to the manufacturer's stated error of indication. However, even with these tests it is not possible to make a statement about the length measurement capability of the machine due to the complicated way in which the uncertainties associated with the CMM combine. Therefore, the length measurement uncertainty derived from a limited sample of measurements cannot be considered representative of all the possible length measurement tasks and certainly not of the measurement tasks the CMM is capable of performing. In effect, the tests do not guarantee traceability of measurement for all measurement tasks performed. The user should be aware of this important fact and develop task-related measuring strategies for each measurement undertaken that will provide the appropriate level of confidence in the overall result. Virtual CMMs can help meet this requirement. Further information on virtual CMMs can be found in NPL report CMSC 01/00 *Simulated Instruments and Uncertainty Estimation* A B Forbes and P M Harris and in NPL Good Practice Guide No.130 *Co-ordinate measuring machine task-specific measurement uncertainties*. CMM verification is the subject of a separate NPL good practice guide *No.42 CMM Verification*.

The sampling strategy for a CMM inspection process is under the user's control whereas the accuracy level is associated with the machine and the software. Over the last decade the advancement of hardware and software technology has resulted in machines that are potentially capable of high accuracy measurements. However, the inspection quality and hence the confidence in the result can be impaired by improper measurement strategies.

The selection of a measuring strategy that creates confidence in the result demands skill, experience and attention to detail on the part of the user. This guide sets out to assist the user in identifying the uncertainties inherent in the use of CMMs and advising on the strategies that will provide confidence in the measured results.

In contrast with simple, single-purpose measuring instruments, CMMs are able to measure a wide range of geometrical parameters. For each of these parameters the user may adopt any of a number of measurement strategies. These include the selection of a particular probe and stylus configuration, the number and position of measuring points and the direction and speed of approach of the probe. Both the measurement task and the selected measurement strategy determine the way in which errors are introduced in to the measurement system to influence the uncertainty associated with the measurements.

## General measurement strategy

The general measurement strategy can be subdivided into a number of tasks that should be followed by the user.

1. **Selection of the features on the workpiece to be measured.**

2. **Definition the workpiece datum feature(s) to be used within the co-ordinate system.**

3. **Selection of the workpiece orientation.**

4. **Selection of the workpiece holding method.**

5. **Stylus system qualification.**

6. **Definition of the probing strategy.**

7. **Programming of the CMM and assessment information recording.**

The following chapters will cover each of these points in turn.

# Selection of the features to be measured

# 2

**IN THIS CHAPTER**

- Features to be measured
- Workpiece setup
- Repositioning methods

The purpose of chapter 2 is to give the reader an introduction to some of the considerations necessary when setting up a part for measurement. Identification of the features for measurement will be discussed along with workpiece setup and access considerations. Finally, accuracy improvements using repositioning methods will be discussed.

## Features to be measured

In general, production and functionality requirements will determine which features require measurement. In some cases a component could have some features that (a) cannot be measured on a CMM due to accessibility problems, (b) are impractical to measure such as circular sections of small arc length and (c) could be more cost effectively measured using other instruments. Consideration should be given to the minimum number of surfaces that require measurement by a CMM in order for the user to establish the accuracy of the workpiece. This information as to whether a full or partial inspection is required may appear on the drawing.

## Workpiece setup considerations

In general, it is important to establish a strategy that requires, if possible, a single set up of the workpiece for the measurement of all relevant features. If more than one set up is used, there is the possibility of operator error degrading the measurement process and hence reducing the confidence in the results. However, on the other hand, using more than one set up can enhance the accuracy by minimising the need for complicated stylus arrangements. In general the user should use the minimum number of set ups for the measurement of a workpiece. One set up should be the aim. The way in which any measurement is made is generally a compromise between speed and accuracy. To achieve the accuracy required for some tight tolerances may require multiple set-ups and hence longer measurement time. Always bear in mind the target tolerance. The following example illustrates this point.

In figure 1, the distances between the spheres A, B and C are required. It is possible to measure these distances in one set up as shown. The distance BC will probably have a smaller uncertainty than the other two lengths as use is made of only one machine axis for this measurement. Measurement of length BA and AC require the use of two machine axes hence the likelihood of a larger uncertainty. However, rotation of the item so that the other lengths fall in place of length BC, means that with three set-ups the lengths will be known with smaller uncertainty because the same scale and location are used for each measurement.

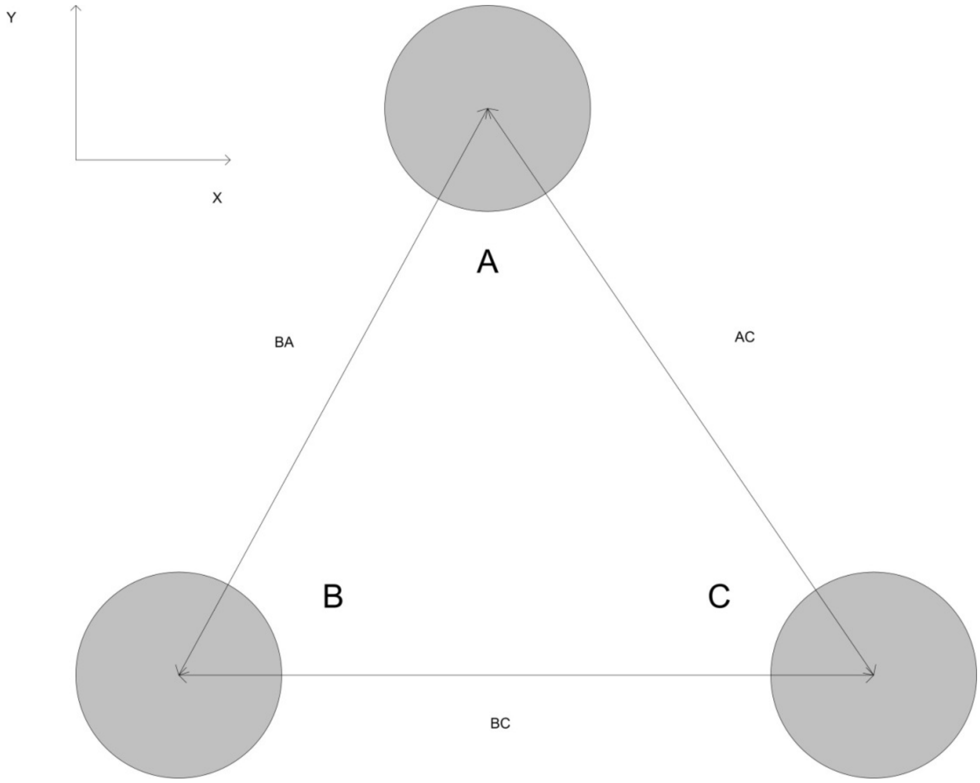



**Figure 1 Using multiple setups to measure a component.**

## Repositioning methods

A further extension to the idea covered in the section on *Workpiece setup considerations* is the technique known as re-positioning. With this technique, reference artefacts, such as spheres, are attached to the item being measured. The item is then measured using multiple set-ups. For each set up, the positions of the reference artefacts are also measured. Software is then used to collate all the data from the various set-ups into the same frame of reference (co-ordinate system). NPL report CLM2 *Measurement of Artefacts using Repositioning Methods* contains further detail on the repositioning technique.

## Chapter summary

- Use minimum number of set-ups
- Use only one axis for critical dimensions if possible
- Choose the most appropriate machine for the job
- Make use of repositioning techniques where necessary

# Define the workpiece datum to be used within the co-ordinate system

# 3

**IN THIS CHAPTER**

- Datum features on drawing
- Changing the datum
- Measuring small features

A datum is a reference surface, plane, line or point used to facilitate the definition of features on a part. A datum is usually a locating or positioning feature used for (non-CMM) measurement. A datum is also the origin from which the location or geometric characteristics of a part are established. A datum feature is an actual feature of a part that is used to establish a datum and can be a surface, an axis or a median plane. A functional datum feature is a surface on a component, which is of importance to the function of the component in an assembly. Definition of a datum can be a complicated subject and the reader is referred to standards ASME Y14.5M, ISO 1101 and ISO 5459. NPL Good Practice Guide No.79 *Fundamental Good Practice in the Design and Interpretation of Engineering Drawings for Measurement Processes* covers datum usage more fully. Understanding the datum is important as large errors can result from using an inappropriate datum.

In the preparation for measurement, using a CMM, of a component based on a detail drawing derived from the assembly drawing, it is necessary to identify functional datum features - those features that are critical in the function of the component. These features will have small tolerance dimensions. A component detail drawing must present information in a form that is suitable for manufacture (and inspection), and must show the required manufacturing dimensions that are related to each datum.

## Datum features on drawing

In most cases, the co-ordinate system for measurement should make use of datum features identified in drawings or technical documents relating directly to the workpiece.

The datum features can be identified from the component drawing or CAD model. The datum features are normally indicated on the technical drawing as a filled or an open triangle. The identification contained within the box is normally a capital letter. The letter will occur in the feature control frame of tolerances related to this datum. The feature control frame should identify all the datum features required. When measurement takes place, it is important to be able to create a co-ordinate system related to the component. The terminology used to identify the datum features in geometrical tolerancing is as follows.

1. *The primary datum* - this is defined as a feature or features used for the levelling of the component normally on a surface or an axis.
2. *The secondary datum* - this is defined as a feature or features used for the rotation of the component part relative to the primary datum.
3. *The tertiary datum* - this is defined as a feature or features used to complete the co-ordinate system in relation to the primary and secondary datums.

However, a workpiece datum can be developed from theoretical points that cannot be measured by the CMM; these are usually points indicated on mating part surfaces or co-ordinates used in a large assembly.

**NOTE**

It is not usually the prerogative of the designer to decide the details of the machining of a component, although it is often possible to foretell the sequence of some of the manufacturing processes involved. From knowing this sequence the designer can identify the manufacturing datum face(s), and from this, the required machining dimensions.

A datum feature is an important feature - a locating or positioning feature. A datum feature can be a face (a surface) or the centre line of a hole. A functional datum feature is a face, or a hole, in a component, which is of importance to the function of the component.

For example, a cylinder axis cannot be measured, as it does not exist as a physical entity, in this case the user would generally measure a functional aspect on the workpiece such as a face or hole diameter and relate this position to the intended position of the centre line.

In figure 2, to determine the dimension (*x*) the user would first set the relevant co-ordinate system and using the datum face would measure the hole to establish the theoretical centre-line of the hole.

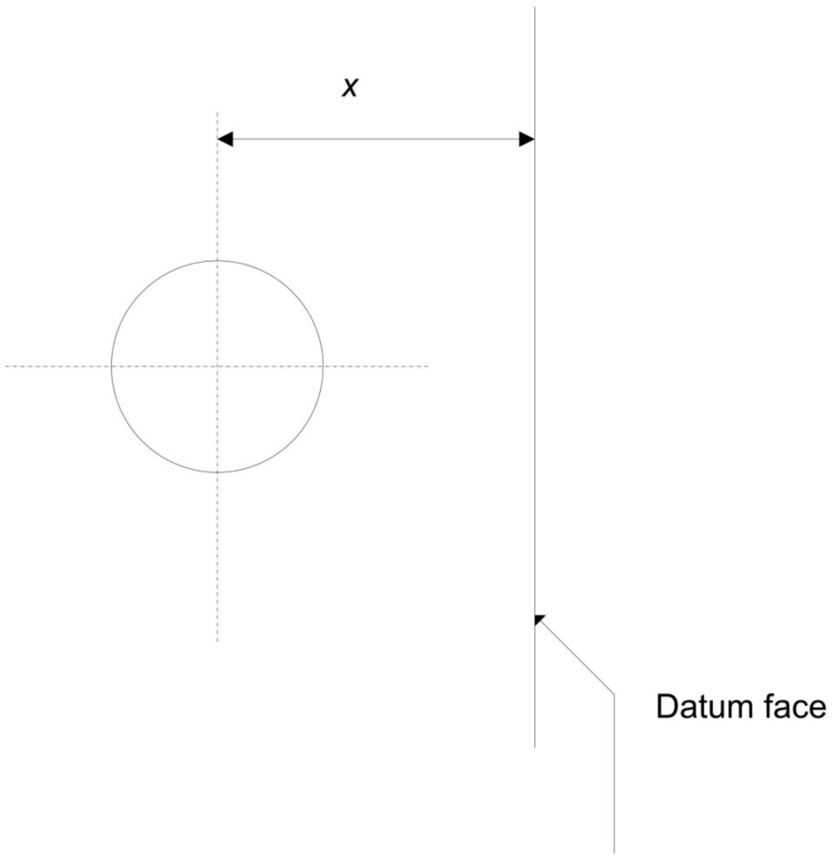



**Figure 2 Finding the centre line**

When creating a datum it is preferable to choose the surfaces that are used in the manufacturing process to hold the workpiece as datum features. This choice relates the inspection results directly to the manufacturing process.

The features of any workpiece can be defined in two ways, relative to a datum position or positions, or relative to one another. The engineering drawing should clearly define the co-ordinate system.

The datum features define the co-ordinate system. The most common co-ordinate system in use is the Cartesian system (figure 3). It comprises three linear axes that intersect at the system origin. The three axes are mutually perpendicular and are usually designated X, Y and Z.

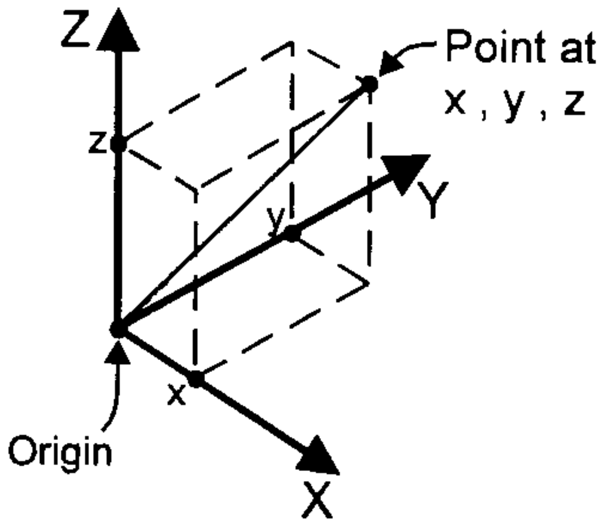



**Figure 3 Cartesian co-ordinate system (© D. R. Coleman & T. F. Waters)**

Lord Kelvin's principle of kinematics states that 'a body free to move in space has six degrees of freedom'. There are three degrees of freedom linearly along the X, Y and Z-axes and three degrees of freedom in a rotational sense around the X, Y and Z-axes. Therefore, to define a co-ordinate system a minimum of six measurement points are required (Figure 4).

To define a datum (co-ordinate) system for a rectangular part with flat surfaces that has its origin in one corner would require six contact points (figure 4). Three points are required to define a flat surface or plane (the XY plane – primary datum A), a further two points are required to define a line which lies on the XZ plane (secondary datum B) and a final point in the YZ plane (tertiary datum C).

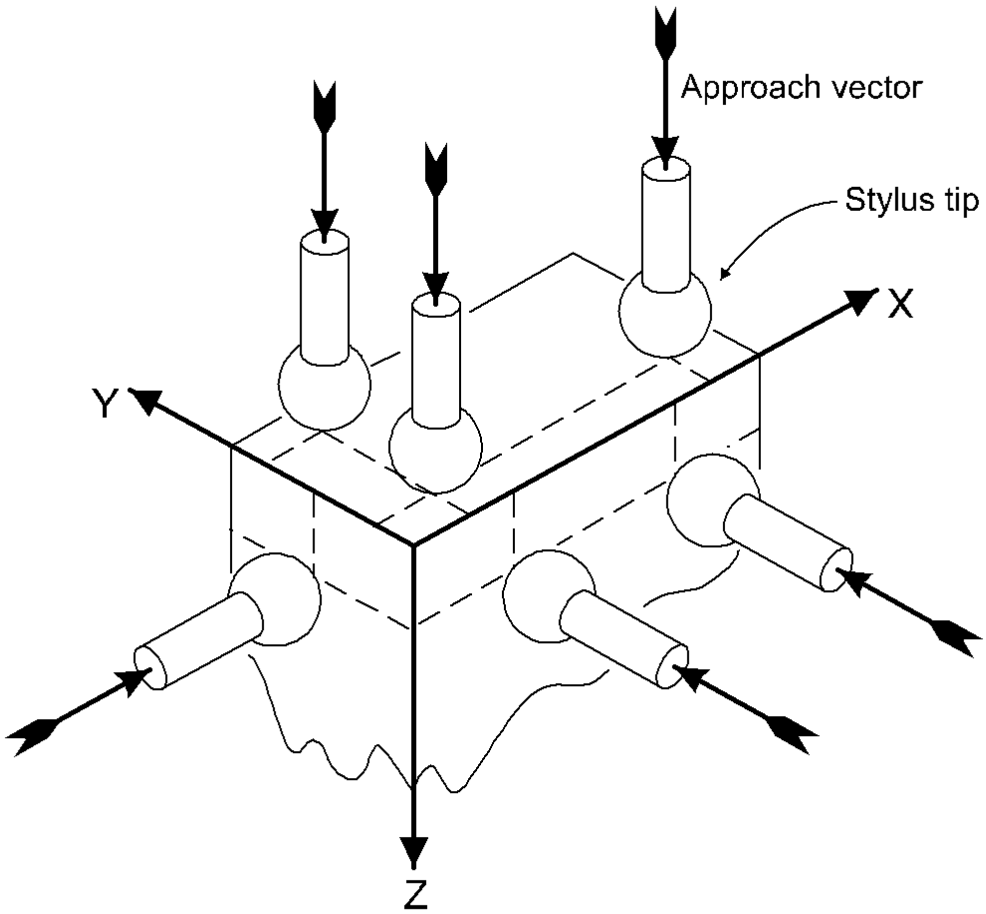



**Figure 4 The six contact points needed to create a coordinate system (© D. R. Coleman & T. F. Waters)**

Note that the three planes are created to be mutually perpendicular and the point of intersection of these three planes is the origin of the system $x = 0$, $y = 0$ and $z = 0$.

Each datum for a component, and their precedence, should normally be specified on the product drawing. If the user decides on an alternative datum, the effect on the results can be quite dramatic.

When considering the features that are required for the creation of the datum on the component, the user should determine whether the primary datum is a surface or an axis. The next stage is to determine the secondary and tertiary datum and from these the co-ordinate system to be used for the measurement strategy can be set. A document on datum systems is available form NIST – *A conceptual Data Model of Datum Systems Journal of Research of the National Institute of Standards and Technology Volume 104, Number 4, July-August 1999*. It can be downloaded free of charge from the NIST web site.

# Changing the datum

### *Introduction*

It should not be necessary for anyone using a drawing or technical documentation to have to interpret the presented information, the user should not have to carry out any calculations or adjustments in order to complete the activities relating to the component measurement. However, in some cases it may be necessary for the user of a CMM to relate certain features of the workpiece to a datum not indicated in the drawing or technical documentation. This can be a complex procedure, which will require a number of steps to complete and in the course of which toleranced dimensions may have to be altered. Take care when making such alterations.

### *Procedure*

The procedure to be followed when changing the datum face is a complex one and can be summarised as:

1. decide on the required datum face;
2. decide on the required measuring dimensions (which may also involve deciding that some dimensions will have to be omitted);
3. determine the tolerance for each of the new dimensions to be measured;
4. set suitable limits for all but one of the required dimensions; and
5. determine the limits of the final dimension.

### *An example*

The example given here relates to changing a datum for a machining operation but this example equally applies to measurement. In the preparation of a component detail drawing, it is necessary to identify functional datum faces and functional holes, these faces and holes will be critical in the functioning of the component. These features are recognisable, as they will have small tolerance dimensions. In figure 5, there are four functional features (as shown in figure 6).

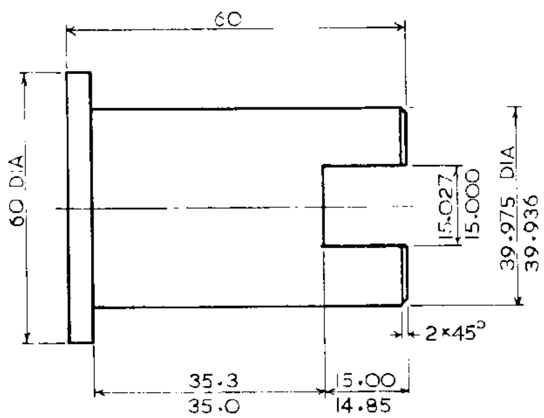



**Figure 5 The component drawing**

The functional features are:

1. The 39.975 mm/39.936 mm limits indicate that this diameter is to be a running fit in a mating component.
2. The 15.027 mm/15.000 mm limits indicate an important internal feature.
3. The two linear dimensions 35.3 mm/35.0 mm and 15.00 mm/14.85 mm are functional dimensions in that they indicate that the bottom face of the groove is functionally important, both to the right-hand end face of the component and the right-hand face of the 60 mm diameter, therefore the bottom of the groove is a functional datum face.

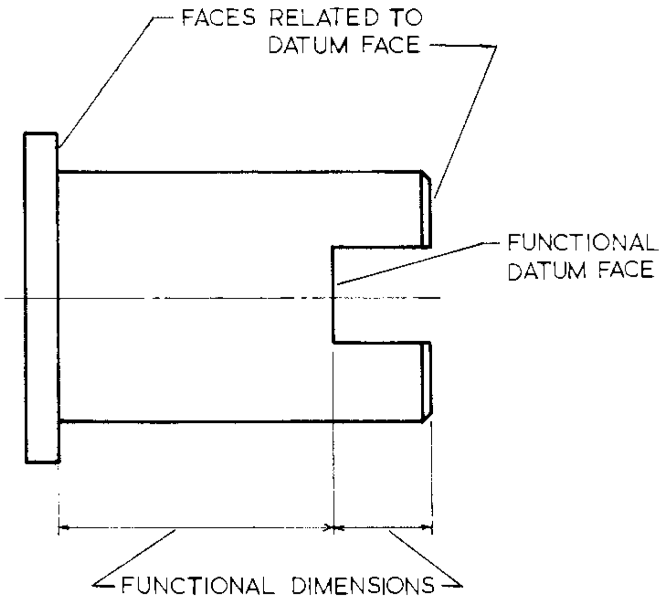



**Figure 6 The component functional features**

The manufacturing sequence will commence with a turning operation followed by a grooving operation. Therefore, for the turning operation a direct dimension, with appropriate limits, is required for the length of the of the 39 mm diameter. These limits cannot be obtained by adding the two chain dimensions together (35.3 mm/35.0 mm and 15.00 mm/14.85 mm).

The manufacturing datum face for the turning operation has to be the right-hand end face of the component. This now will require a changing of the datum face, which as stated above was the functional datum face at the bottom of the groove.

When the datum face is changed there is, inevitably, a reduction in tolerance of one, or more, dimensions. In addition, never duplicate dimensions. This means that in showing the new dimension for the 39 mm diameter one of the chain dimensions 35.3 mm/35.0 mm and 15.00 mm/14.48 mm must be omitted from the drawing.

In the interests of obtaining the largest tolerance possible for the dimensions involved, the dimension having the largest tolerance should be omitted. That is to say, the 35.3 mm/35.0 mm dimension, because the tolerance of the omitted dimension (35.3

mm/35.0 mm), that is to say, 0.3 mm, is the total tolerance for the remaining, controlling, dimensions (50.15 mm/50.00 mm and 15.00 mm/14.85 mm).

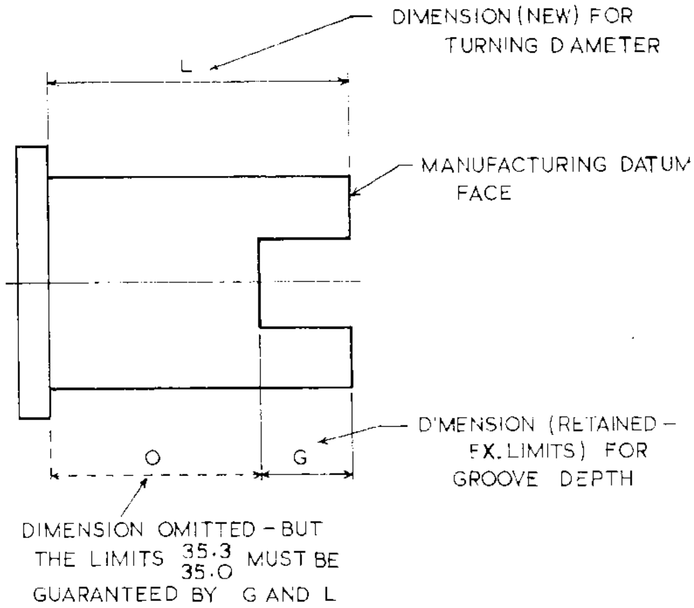



**Figure 7 New datum**

In summary:

1. The manufacturing datum face, for both processes, is the right hand end face.

2. Dimension L for turning, dimension G for groove depth, the 35.3 mm/35.0 mm dimension omitted.

3. Tolerance of the omitted dimension is 0.3 mm. Let the tolerance (limits) for G remain as 0.15 mm. Therefore, tolerance for L is 0.15 mm

4. Limits for G remain unaltered that is to say 15.00 mm/14.85 mm.

5. Determine limits for L as follows: to ensure that the limits of omitted dimension O are not exceeded (figure 7), use is made of a diagrammatic representation of the limits L and G in terms of the limits of O.

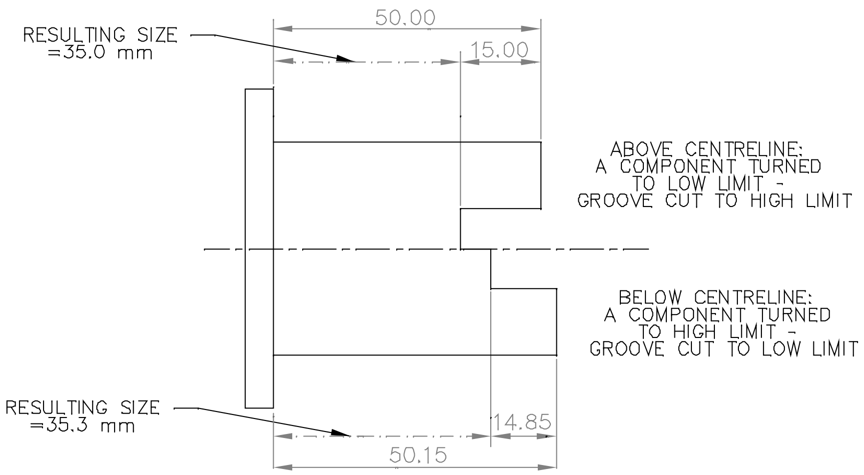



**Figure 8 Verification of limits**

When O is minimum, then L is minimum and G is a maximum.
When O is maximum, then L is maximum and G is a minimum.

Hence:

L min = 35.0 + 15.0 = 50.0 mm
L max = 35.3 + 14.85 = 50.15 mm

Verification that the limits of dimension O, although now omitted from the drawing, will not be exceeded, is shown in figure 8.

The component will now require re-dimensioning to suit the requirements of the operation sequence (figure 9). Figure 10 and figure 11 show the initial and final tolerances.

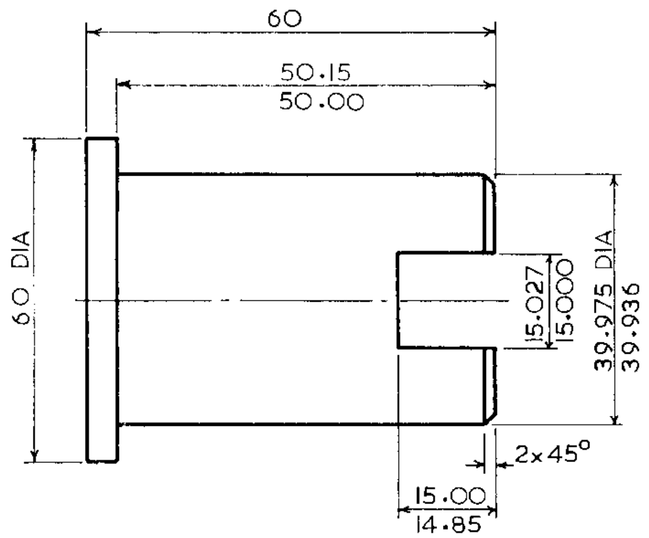



**Figure 9 The new dimensions**

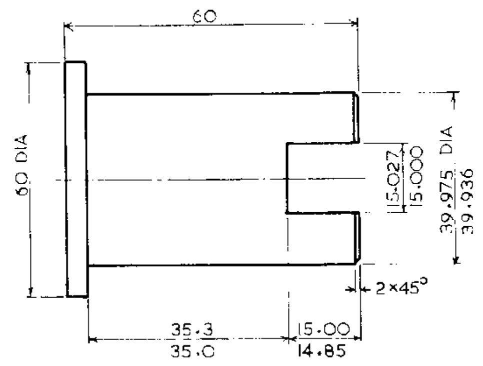



Figure 10 Initial tolerances

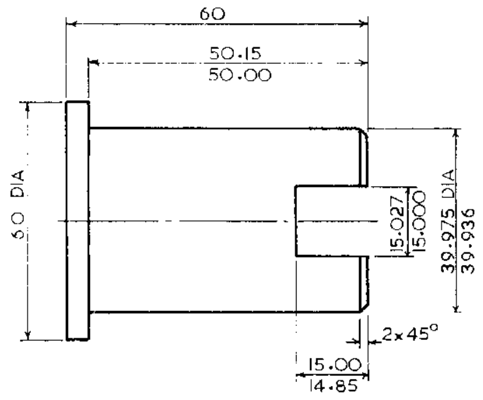



Figure 11 Final tolerances

The tolerance reduction that occurs when the datum face is changed is shown in the new dimension for the turning operation, where the tolerance of 0.15 mm is half the tolerance of the omitted dimension.

## Measuring small features

Take care when alignment is made on small features. Do not use small features as the primary datum. An example of this is aligning the end face of a long thin cylinder. Any small error in aligning the end face (perhaps due to the face geometry) will produce a progressively greater error when checking the axis of the cylinder, that is to say, the longer the cylinder the greater the error.

In cases where alignment is required on small features, the user should assess the functionality of the workpiece and align a chosen surface or datum in an appropriate manner to avoid unnecessary geometric errors. In the case of the cylinder end face, it may be more appropriate to align the outer diameter of the cylinder and probe the end faces from this aligned datum. Note that the use of a non-specified datum might cause errors in the results. A non-specified datum is one that has not been specified by the designer and which the user has, in the interests of accuracy or ease of measurement, substituted a functional datum feature as new datum. Since in some cases the use of an alternative datum may be unacceptable the user should discuss the implications of changing a datum with the design department.

## Chapter summary

- Use datum on drawing if possible
- Take care when changing datum
- Avoid using features of small area for alignment

# Selection of the workpiece orientation and holding method

# 4

**IN THIS CHAPTER**

- Selection of the workpiece orientation
- Selection of the workpiece holding method

This chapter considers the importance of selecting the workpiece orientation and choice of holding methods.

## Selection of the workpiece orientation

Once the measurement and datum features have been determined, the next step is to decide on the orientation of the workpiece within the measurement volume of the CMM. The major consideration is to ensure the accessibility of the surfaces and features that have been selected for probing. As stated in section *Workpiece setup considerations* the user should ideally seek a single set up for the entire strategy.

When using a CMM it is not normal to hold the workpiece on the datum features; it is these features that require probing and they therefore need to be free of any obstruction.

The user should be aware of the functionality of the workpiece and, in some cases, it is advisable to align the critical feature of length/size along one of the CMM's axes. Aligning the artefact in this way will ensure the use of only one axis for measurement, therefore eliminating the uncertainty due to the other axes.

## Selection of the workpiece holding method

### *Measurement force*

When choosing a holding method the user should be aware of the effect of the probing force. CMMs operate at very low probing forces, usually in the region of 0.05 to 0.2 N. However, this is the force at the time of measurement. The CMM may subject the item to a force of up to 3 N during the measurement process irrespective of the target measurement force as many CMMs have an initial probing force far higher than the target measuring force.

### *Heavy items*

If the part is sufficiently heavy then it may be possible for it to be located on the machine table in a stable manner without the need for any holding devices. The user should note that measurement in a free state, that is to say no use of securing medium of any kind, is now a requirement under some geometric dimensioning and tolerancing standards (ASME Y14.5M-1994). However, be aware that heavy loads may distort the geometry of the machine.

### *Light items*

For small, light parts use Plasticine, modelling clay or instrument wax as a holding material, although the user should ensure that after completion of the inspection all traces of Plasticine or clay are removed from the table and component. Magnetic or vacuum chucks are alternative holding methods.

In some cases, it will be necessary to mechanically clamp a workpiece to the CMM table or jig. The user should be aware that clamping forces could distort the true shape of the part and therefore take care not to over tighten the clamps. It is good practice to use of cork sheet between the workpiece and the clamps. Write the Computer Numeric Control (CNC) program in such a way as to avoid collision with the clamps and notes on the clamping locations should be kept with the CNC program.

### *Fixtures*

Work- holding kits are available that enable the user to fabricate simplified, purpose-built fixtures in which to locate workpieces.

For more complex set ups modular workpiece clamping systems (figure 12), such as Swift-Fix or Allufix®, should be considered. Another example of good holding practice is to use purpose-made fixtures for the part to provide ease of use for location; this workpiece holding technique has the advantages of a short set up time and measurements that can be taken in one particular part of the CMM table where the performance of the CMM is well known.

When using purpose-made fixtures the user should ensure that the fixture is clean, the workpiece is located correctly, clamping forces do not distort the workpiece and that all features requiring measurement are accessible.

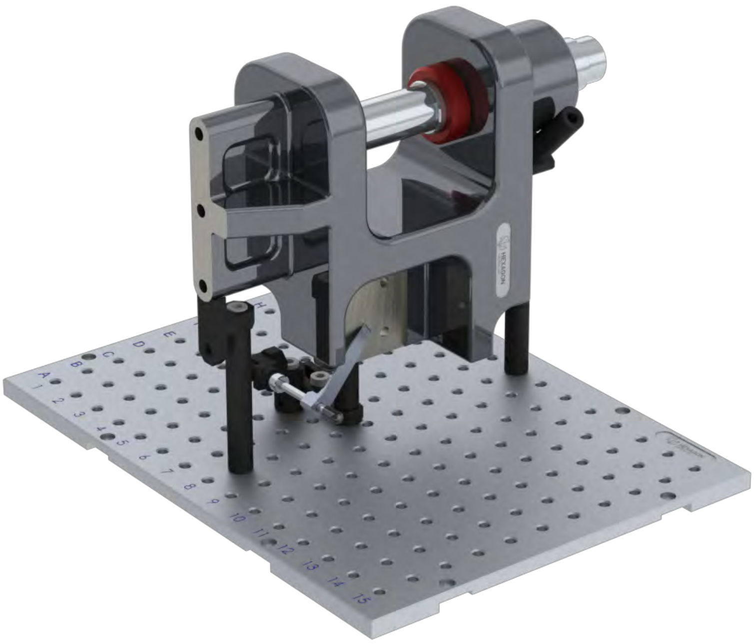


**Figure 12 A component held in a workpiece holding kit (courtesy of Hexagon Metrology)**

### *Adhesives*

Workpieces can also be secured directly to the table by the use of a hot glue gun containing an appropriate glue stick – for obvious reasons glues recommended for use on granite should not be used on granite worktables. Secure the component by tacking the edge of the component in direct contact with the table. The advantage of this method is that the workpiece does not undergo distortion by clamping forces. The user should ensure that all features requiring measurement are accessible; it must be borne in mind that it will not be possible to gain access to the feature in direct contact with the table. On completion of measurement, remove the glue by the application of a suitable solvent. The main disadvantage of using this method is that the user will need to orientate the component by visual means. Only use glue guns if:

(a) there is no significant change in the room temperature whilst the component is glued to the table, or
(b) the expansion coefficient of the part being measured is close to that of the worktable.

If the workpiece and granite temperatures increase, their lengths will increase at different rates. Since the base of the part is glued to the table, it cannot expand resulting in part distortion. Clearly, changes of temperature will lead to distortion of the part or the table if the coefficient of thermal expansion of the part and table are significantly different.

Instrument wax is an alternative to glue and is heated and softened by hand and applied to the edge of the workpiece in contact with the table in the same way as the glue is applied. However, since instrument wax can cause movement of the workpiece position for about an hour after application, do not take measurements until this period has elapsed.

The use of restraint materials that are elastic by nature (such as silicon rubber) allow expansion of the workpiece and are recommended.

### *General*

In any clamping arrangement, do not over-constrain the workpiece. Ideally, one would only clamp at one point to minimise distortion, however, such clamping may allow the part to rotate during measurement. Light clamping and the use of a material such as rubber or cork between the workpiece and clamp will help to minimise distortion and avoid damage to the workpiece.

## Chapter summary

- Do not over constrain the workpiece
- Do not clamp so as to distort or damage the workpiece
- Be aware of thermal problems
- Avoid the use of glue if possible

# Stylus system qualification

# 5

**IN THIS CHAPTER**

- Basic stylus system qualification
- Additional checks
- The choice of stylus
- Comparison (substitution method)

Stylus system qualification and the choice of stylus are of paramount importance when deciding the measurement strategy. This chapter briefly covers some good practice in this area.

## Basic stylus system qualification

NPL good practice guide on probing (No. 43) covers stylus system qualification. However, the following is a brief description of some key points.

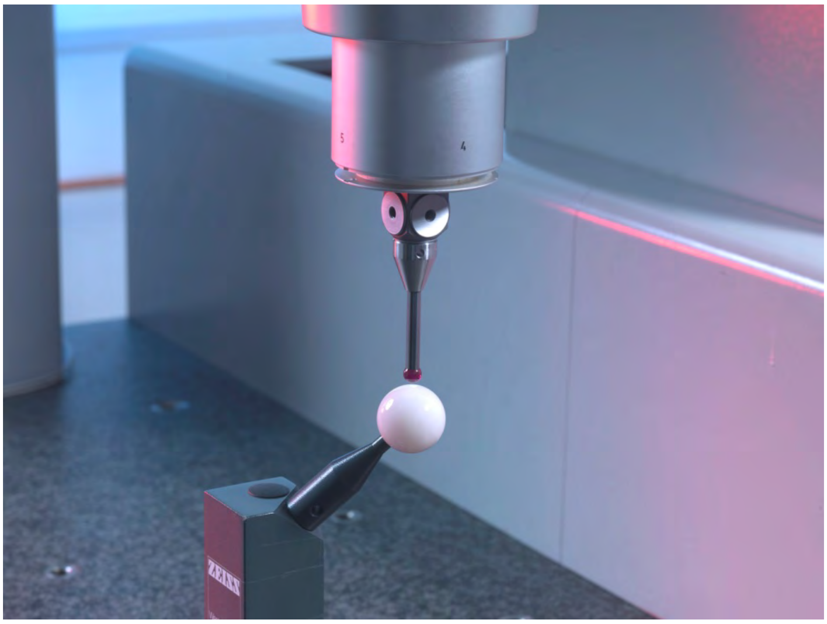


**Figure 13 CMM stylus system qualification of a spherical tipped stylus using the CMM's reference sphere.**

Stylus system qualification should be undertaken for every combination of stylus and probe body that is likely to be used during the course of the inspection of a particular component. The stylus tip should be qualified against a reference sphere (figure 13) or other recognised calibration artefact. It is most important to keep the stylus tip and qualification artefact clean at all times. The user should adopt a task-related measuring strategy, that is to say the dimensions of the stylus tip should be qualified under the same conditions as those under which the workpiece will be measured. Ideally, the direction and speed of approach should be the same for both qualification artefact and workpiece.

It is usual to use a certified reference sphere for qualification purposes. During qualification, the probe stylus is driven perpendicularly onto the surface of the sphere in several planes. By qualifying the probe in suitable directions, the effect of pre-travel variation of a touch trigger probe over 360° can be significantly reduced.

Careful qualification of the stylus will improve the accuracy of some measurements, such as features of size. By increasing the number of points used in the stylus tip qualification, the resulting effective stylus tip diameter will generally be more accurate.

It good practice that for small diameter stylus tips a small reference sphere should be used, for example to quality of a 1 mm diameter tip use an 8 mm diameter reference sphere. The user should also ensure that if more than one reference sphere is available the value that is entered into the software definitely relates to the sphere in use. A common error is the use of the wrong value for the reference sphere size; if this happens then the probing result output will be incorrect.

The user should maintain a record of the historical data of probe qualification and ensure that after qualification a comparison is made between the data being produced and that in the historical record. Ask the question:

*Does this probe normally output this value? If not why has the value changed?*

If the values obtained from the probe qualification have altered significantly then the user should take action to investigate the reason. Examine the stylus and reference sphere for cleanliness, and ensure that the value entered into the software for the reference sphere diameter corresponds to the reference sphere currently being used and that the probing strategy is the same as that used to establish the historical data.

It is possible to use gauge blocks and ring gauges in order to qualify the probe stylus. However, a sphere is preferable since all probing directions are taken into account.

## Additional checks

Gauge blocks can be used to determine the probe hysteresis of touch trigger probes - an error that is a consequence of the direction of the previous trigger and following the reseating of the probe. For analogue probes, the test can detect errors in probe qualification. Perform the by probing the inner and outer faces of a gauge block stack (figure 14). The difference between the two readings should be zero; however, any difference in the actual results obtained will indicate the degree of uncertainty associated with the particular probing system in use.

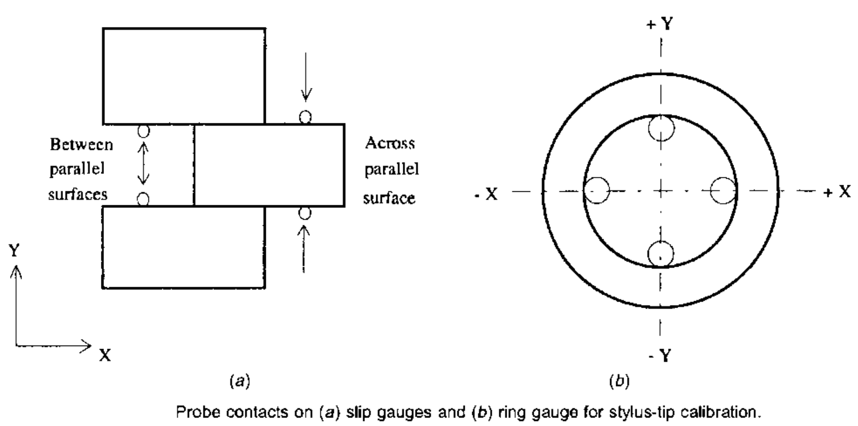



**Figure 14 Probe contacts on gauge blocks and ring gauge (courtesy F M M Chan *et al*)**

The gauge block check above will also reveal any errors in determining the radius of the particular stylus in use. For example if the size of the middle gauge block is 10.000 0 mm and the measured dimensions are 9.998 0 mm (external) and 10.002 0 mm (internal) this suggests that the probe radius is incorrect by 0.000 5 mm.

If $M_E$ is the measured dimension externally, $M_I$ is the measured dimension internally, $G$ is the calibrated size of the gauge block, $r$ is the actual probe tip radius and $r_q$ is the qualified probe tip radius then

$$M_E = G + 2r - 2r_q$$
$$M_I = G - 2r + 2r_q$$

and

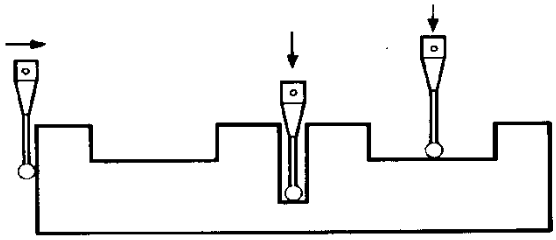
$$M_E - M_I = 4r - 4r_q$$

The difference between the two measurements is four times the error in the probe radius. However, note that the non-parallelism of the gauge block faces may introduce errors.

The probing sphere tip will always make contact perpendicular to the surface and the stylus should always approach the surface along this line. During measurement, the probe should be moved in the same direction as the measurements made during the qualification stage. For example if a gauge block is mounted on the machine for measurement so that the gauging faces are 45° to the X-axis then make sure that the qualification of the probe includes probings in the same direction as will be used for probings on the gauge block surface.

## The choice of stylus

The stylus tip diameter should be as large as possible; with larger balls, surface finish has less effect on the measurement gaining more flexibility due to the ball/stem clearance. The largest tip diameter that can be used is determined by the smallest diameter hole to be measured (should the workpiece contain holes). Each stylus has an Effective Working Length (EWL). This length is the penetration achieved by the tip before the stylus shaft (stem) fouls on the component (figure 15). Usually the larger the stylus tip is the greater the EWL.



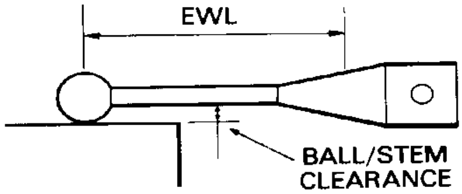



**Figure 15 (Effective Working Length source Renishaw Technical Specification Manual)**

CMM Probing Good Practice Guide No. 43 covers stylus choice in more detail.

## Comparison (substitution method)

The measurement of a traceable reference artefact will permit the errors associated with a specific measurement task to be estimated. This procedure allows the errors associated with the parameters of a measured workpiece to be estimated directly. Because of the complex error structure of the CMM, a calibration of this kind is only valid for measuring workpieces that are nominally identical to the reference artefact used, measured in the same location and using the same measurement strategy. Provided reference artefacts (calibrated working standards) are available that are nominally identical to the workpiece this type of strategy can achieve high accuracy with relatively little effort. This type of strategy is referred to as the Comparator Principle and is relatively straightforward. The reference artefact is measured several times by the CMM (it is good practice to make small changes in the location of the object and the measurement strategy to establish the sensitivity of the measurements to these effects). Once calibrated in this manner the workpiece can be measured with a high degree of confidence. International standard ISO 15530-3:2011 *Geometrical product specifications (GPS) -- Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement -- Part 3: Use of calibrated workpieces or measurement standards* covers the use of a calibrated workpiece. In particular, section 7.4 covers the substitution method.

## Chapter summary

- Qualify the probe regularly
- Perform additional checks against known artefacts
- Pay attention to stylus choice

- Consider the use of the substitution method

# Definition of the probing strategy

# 6

**IN THIS CHAPTER**

- Introduction
- Distribution of points
- The “AD HOC” approach
- The scientific approach
- Partial features and partial arcs

This chapter covers the important topic of selecting the number and distribution of contact points on workpieces that are a combination of standard geometric features such as planes, circles, straight lines, cylinders, cones and spheres. The geometry of a feature can be determined by the fitting of a substitute element to those measured points and the number and distribution of these points is important to make sure the calculated features adequately represent the surface being measured.

## Introduction to probing strategies

A machined workpiece is often a combination of standard geometric features such as planes, circles, straight lines, cylinders, cones and spheres. The geometry of a feature can be determined by the fitting of a substitute element (associated feature) to a number of measured points.

For measurement purposes, there are a mathematically defined minimum number of contact points (figure 16 and table 1) that must be used when fitting an element to a geometric feature. For example, two points define a line and three points define a circle. However, using three points for a circle will give no information on form error. For practical purposes, it is usual during CMM operation to make more than this minimum number of points so that any geometric error in the surface can be determined (table 1). It is not necessary for the points to be equally spaced over the surface but uniform coverage should be aimed for. In fact, it is recommended that equally spaced points are not used. Extreme distributions are however not recommended.

The set of measured values made on the workpiece form the data input to the CMM software in which calculations are carried out to determine position, size and departure from nominal form. To obtain reliable results the data gathered should be representative of the geometric feature being probed. Too few data points or data points that are inappropriately distributed may provide an unreliable reference from which to determine the result.

It must be borne in mind by the user that the greater the number of appropriately distributed measured points the more reliable the assessment is likely to be. However, the larger the number of contact points used the longer the time needed to measure a feature. It is necessary for the user to exercise economic judgement between the accuracy required of the measurement process and the speed at which feedback of the results are required. In addition, for manual and articulated arm CMMs the extra measurement time may lead to increased operator fatigue and consequent mistakes.

The following table is an extract from BS7172: 1989 and recommends the following minimum number of points per feature:

**Table 1 Number of contact points required for various geometric features**

| Number of contact points required | | |
|---|---|---|
| **Geometric feature** | **Mathematical minimum** | **Recommended minimum** |
| Straight line | 2 | 5 |
| Plane | 3 | 9 (Approximately three lines of three) |
| Circle | 3 | 7 (To detect up to six lobes) |
| Sphere | 4 | 9 (Approximately three circles of three in three parallel planes) |
| Cone | 6 | 12 (Circles in four parallel planes for information on straightness)<br>15 (Five points on each circle for information on roundness) |
| Ellipse | 4 | 12 |
| Cylinder | 5 | 12 (Circles in four parallel planes for information on straightness)<br>15 (Five points on each circle for information on roundness) |
| Cube | 6 | 18 At least three per face |

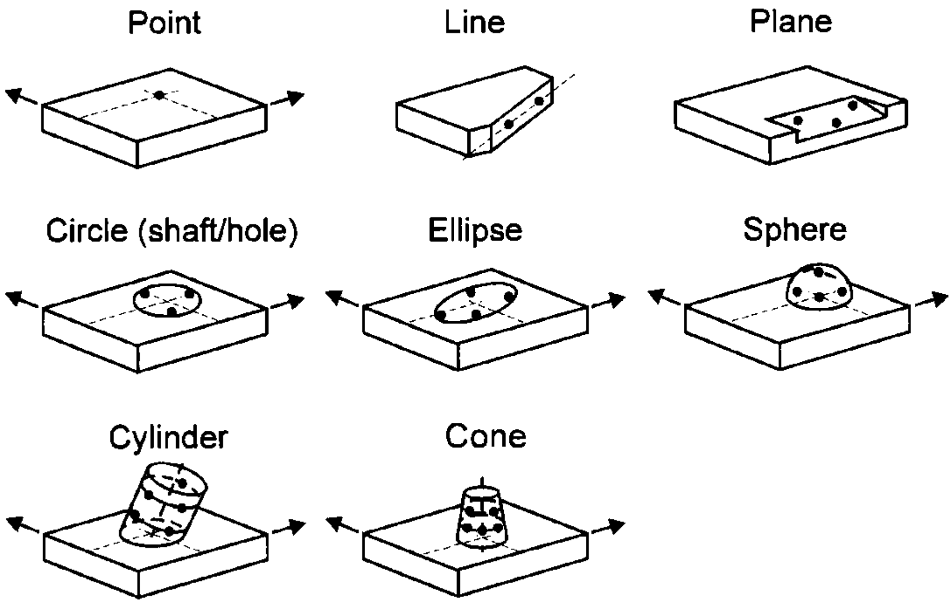



**Figure 16 Defining common geometric features (courtesy Mitutoyo)**

This guide cannot give complete advice on the measurement strategy to use because the points chosen should take into account the nature of the machining process and the intended function of the workpiece. The user of the CMM may know the likely departures from the nominal of a particular workpiece after a particular machining process. An example of this is the type of finish imparted to a component being machined on a lathe when using a round nosed turning tool with a heavy traverse. The finish on the component could possess waviness that can affect the reported diameter. The measurement procedure should take account of that knowledge. Section *The scientific approach* covers this idea in more detail.

The distribution of probing points should normally aim for a uniform coverage of the feature being measured; this will ensure that the input data to the software provides a genuine representation of the geometric feature. However, the user should ensure that the distribution should not be so regular that it has the potential to follow systematic or periodic deformations that are a result of the machining process.

As an example of such deformation, if a nominal circle has three equally spaced lobes, a distribution of six points equally spaced around the circle may fail completely to detect the lobing effect. Thus, a certain amount of randomness in the distribution of points is generally desirable. (Some software applications will automatically generate probing points on a feature for the user; however, these points often have a regular distribution.)

During measurement, the user should constantly question the results obtained and always maintain an awareness of what is normal during a particular measurement strategy. If something looks wrong then action should be taken and the suspect result investigated for the possible introduction of errors during any step of the strategy. It is good practice to keep records of the output of all measurement programmes used and reference made to them when performing repeat measuring strategies.

## Distribution of points

There are two basic approaches to choosing the number and distribution of points:

1. Apply *ad hoc* rules to generate probing points for the various fundamental geometric features.
2. Measure and analyse in detail an actual component representative of the components of interest in order to estimate the form error distribution over the part and hence establish a probing strategy for subsequent use that provides an acceptable balance between economy of measurement and accuracy of the result.

Approach 1 forms the basis of BS7172. It should be emphasised however that the rules described in BS7172 are totally arbitrary and take no account of actual form error.

Approach 2 is scientifically based and is more suitable for parts coming off the production line. A popular article describing this method appears in SSfM's *Counting on IT*, Issue 8 published by NPL.

For an isolated workpiece of which there is no *a priori* knowledge, Approach 1 is an acceptable approach, but there is no guarantee of the quality of the results. The detailed probing part of Approach 2 would be relatively expensive, but reliable.

The section *The “AD HOC” approach* covers the approach detailed in BS7172 whilst section *The scientific approach* covers the scientific approach.

# The “AD HOC” approach

The approach detailed in BS7172 for various elements is summarised in the following sections.

### *Lines*

To achieve a nearly uniform distribution of points on a line segment, divide the line segment into a number of sub-divisions of equal length and one point placed in each subdivision

If the line is likely to suffer from a periodic distortion, the chosen points should not conform to a regular pattern. Therefore, to ensure a non-uniform distribution a point placed in a random position in each subdivision should be selected. To avoid the possibility of choosing points too close together this process can be refined by dividing the line into $3N$-2 subdivisions of equal length and selecting a random point in each of the 1st, 4th, 7th,…, ($3N$-2)nd sub intervals. Figure 17 shows the distribution of points on a line for $N = 5$. One point is chosen at random in each subinterval marked with an asterisk.

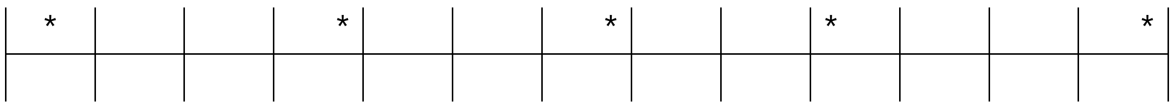


**Figure 17 An example distribution of points on a line**

### *Planes*

To achieve a nearly uniform distribution of ($N$) points on a rectangular segment of a plane, the rectangle should divided into a $N_1 \times N_2$ sub rectangles where $N_1N_2$ is approximately equal to $N$. The sub-rectangles should be as near to a square as possible.

One point should then be placed in each rectangle. If the plane is suspected of suffering a periodic distortion, the chosen points should not conform to a regular pattern. A suitable pattern can be achieved by selecting a random position for each individual point. If it is more convenient to gather data on straight lines across the plane; then these should ideally be irregularly spaced and the points on the lines selected according to the procedure detailed above for line measurement. Figure 18 shows an example where $N = 20$: Choose $N_1 = 4$, $N_2 = 5$ to give $4 \times 5$ sub-rectangles. Note: one point is chosen at random in every sub-rectangle.

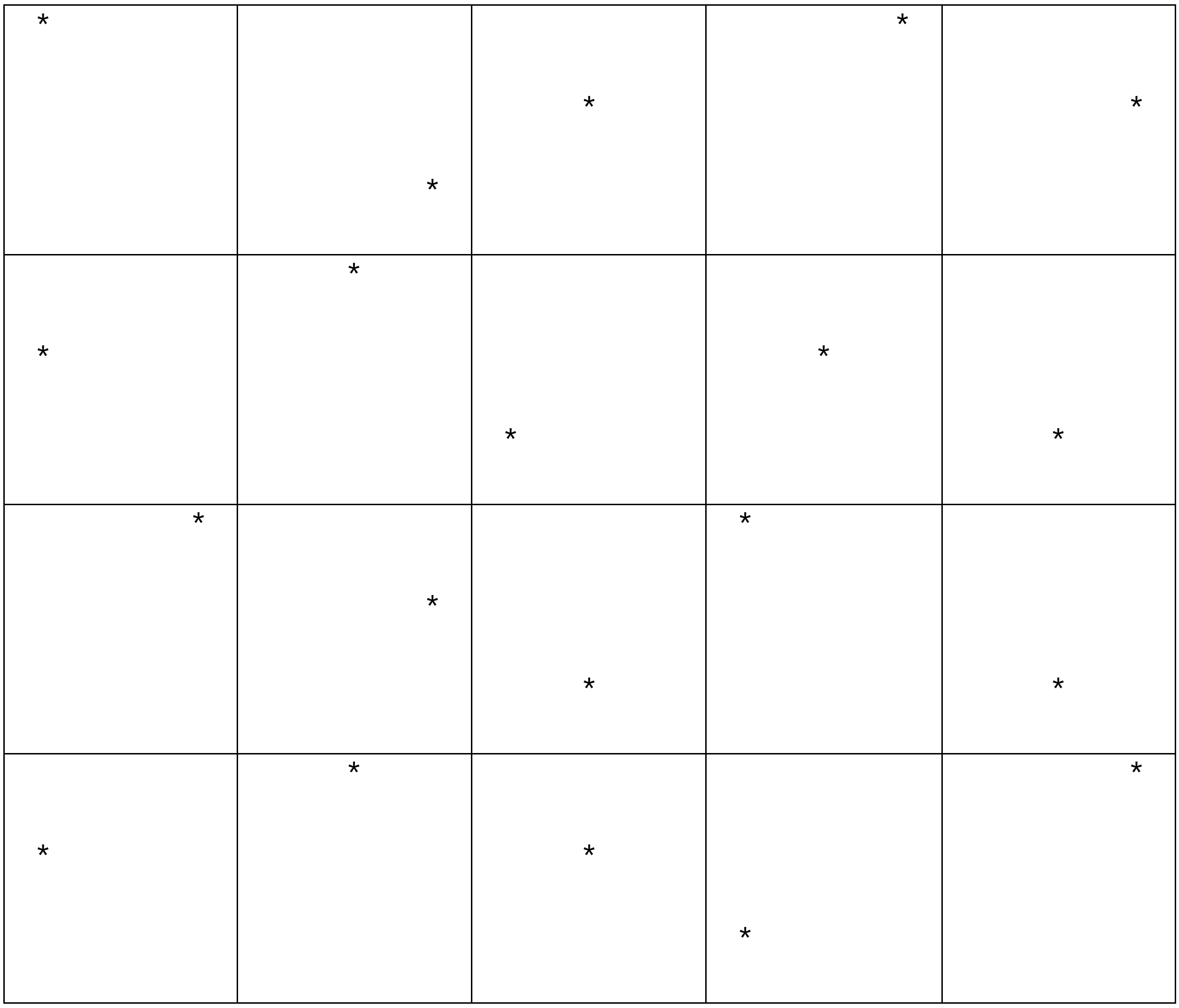


**Figure 18 An example distribution of points in a plane**

If only a small number of points are to be measured the number of sub-rectangles should be doubled and the points distributed in alternate sub-rectangles.

Figure 19 gives an example of this distribution for $N = 10$: Choose $N_1 = 4$, $N_2 = 5$ to give $4 \times 5$ sub-rectangles and chess board distribution of points. Note: one point is chosen at random in every sub-rectangle marked with an asterisk.

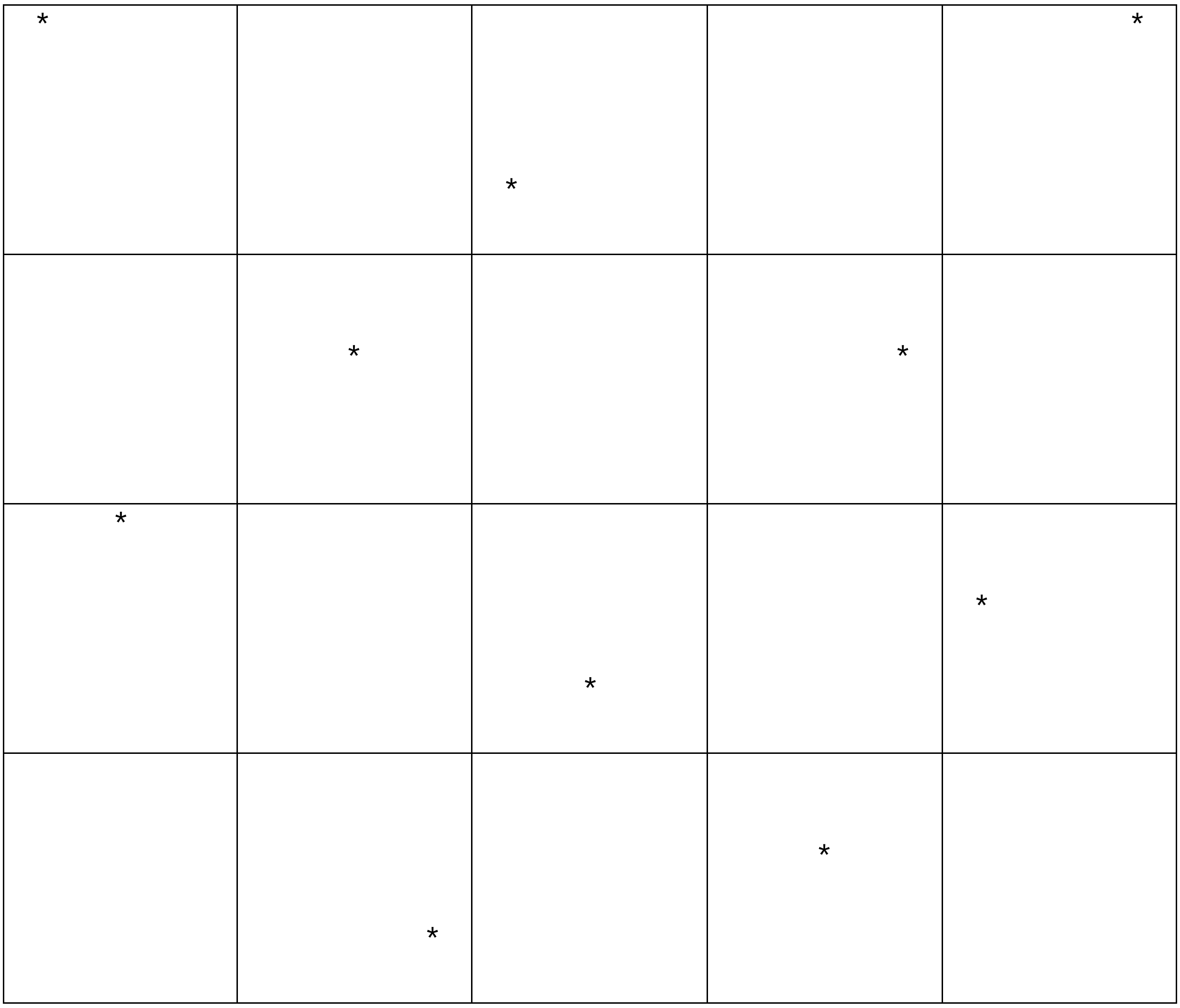


**Figure 19 A ‘chess board’ distribution of points in a plane**

### *Circles*

To achieve a uniform distribution of *N* points divide the circle into *N* equal arcs and place one point on each arc. If the circle is likely to be lobed, it is important not to use a regular distribution. For example if it is known that there is a possibility of the circle having *q* lobes, *N* should always be chosen so that *N* and *q* have no common factor. (*N* should always be chosen to be greater than *q*.) If *N* were divisible by *q* then the information gathered from the measurements would be severely limited.

As an example six points equally spaced on a 3 lobed circle may completely fail to detect the lobing effect (see figure 20). A true circle fits the six points.

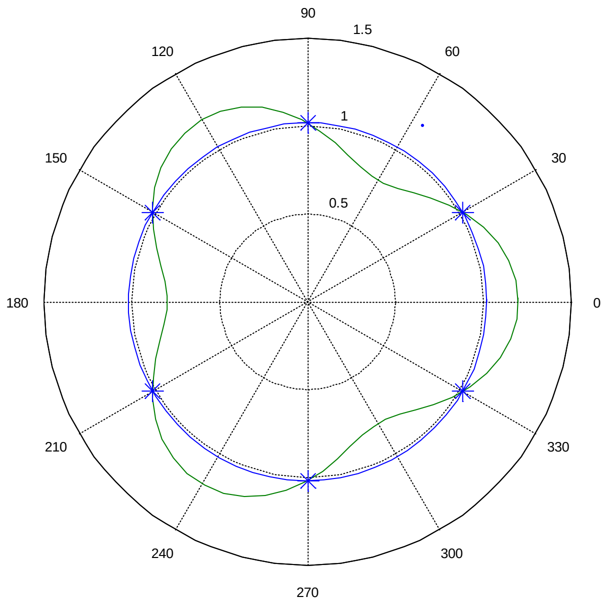



**Figure 20 six uniformly spaced points (*) with complete failure to detect lobing**

Seven points on such a circle will detect at least 79 % of the amplitude of the lobing (figure 21).

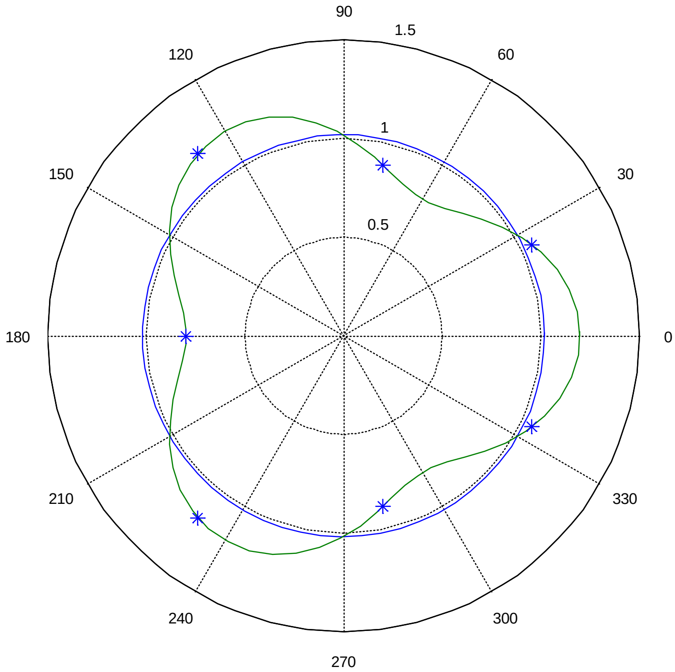



**Figure 21 Seven uniformly spaced points (*) with at least 79 % of the lobing detected**

### *Spheres*

The following strategy for determining the distribution of target points on a sphere achieves a nearly uniform coverage with $N$ points on the surface of the sector of the sphere of radius $r$ enclosed between two parallel planes that are distance $h$ apart.

The procedure is as follows.

First determine $n_c$, an integer close to $\sqrt{Nh/2\pi r}$ and then
$n_p$, an integer close to $N/n_c$.

The standard then states that for each of the $n_c$ approximately uniformly spaced planes parallel to and including the given planes, $n_p$ approximately uniformly spaced measurements should be taken at (or near) the intersection of the plane and the sphere.

For a complete sphere, $h = 2r$, in which case $n_c$ is determined as an integer close to $\sqrt{(N/\pi)}$, with a single point at each pole.

For example:

Consider the case of a sphere where $r$ = 100 mm, $h$ = 150 mm and $N$ = 30.

Using the formula $\sqrt{Nh/2\pi r}$ determine $n_c$ as follows

$$n_c = \sqrt{Nh/2\pi r}$$
$$n_c = \sqrt{30 \times 150/(2 \times \pi \times 100)}$$

Therefore, $n_c$ = 2.67 **choose a value of $n_c$ of 3**

$n_p = N/n_c$,
$n_p = 30/3$
Therefore, $n_p$ = 10.00 **choose a value of $n_p$ of 10**

Figure 23 illustrates the above example where $r$ = 100 mm, $h$ = 150 mm and $N$=30. Choose $n_c$=3 and $n_p$=10

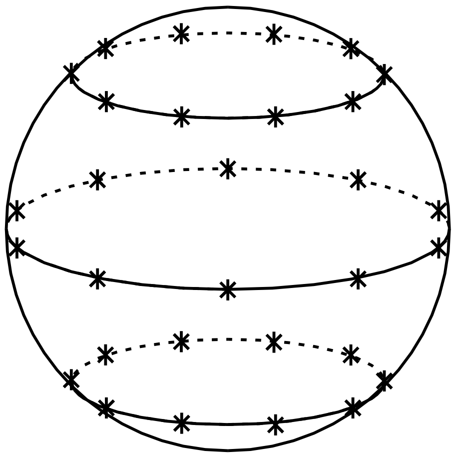


**Figure 22 A distribution of points on a sphere**

### *Cylinders*

To achieve a nearly uniform distribution of a number *N* of points on a cylinder of height *h* and radius *r* is similar to producing target points on a rectangular plane segment as detailed previously in the section on planes. The length of the plane segment will be *h* and the breadth will be$2\pi r$; the distribution for such a plane may be used for the cylinder by wrapping the plane around the cylinder.

A second method is to place the points on parallel circles, with the circles roughly uniformly spaced.

$n_c$, an integer close to $\sqrt{Nh/2\pi r}$ should be determined along with $n_p$, an integer close to $N/n_c$.

$n_c$ is the approximate number of uniformly spaced planes approximately perpendicular to the cylinder axis,

$n_p$ is the approximate number of uniformly spaced measurements which should be taken at the intersection of the plane and the cylinder.

For example:

Consider the case of a cylinder where $r = 10$ mm, $h = 30$ mm and $N = 30$

Using the formula $\sqrt{Nh/2\pi r}$ to determine $n_c$:

$$n_c = \sqrt{Nh/2\pi r}$$
$$n_c = \sqrt{30 \times 30/(2 \times \pi \times 10)}$$

Therefore $n_c = 3.78$ **choose a value of $n_c$ of 4**

Using the formula $N/n_c$ to determine $n_p$:

$n_p = N/ n_c$

$n_p = 30/4$

Therefore, $n_p = 7.5$ **choose a value of $n_p$ of either 7 or 8** (see note below)

Figure 23 illustrates the above example

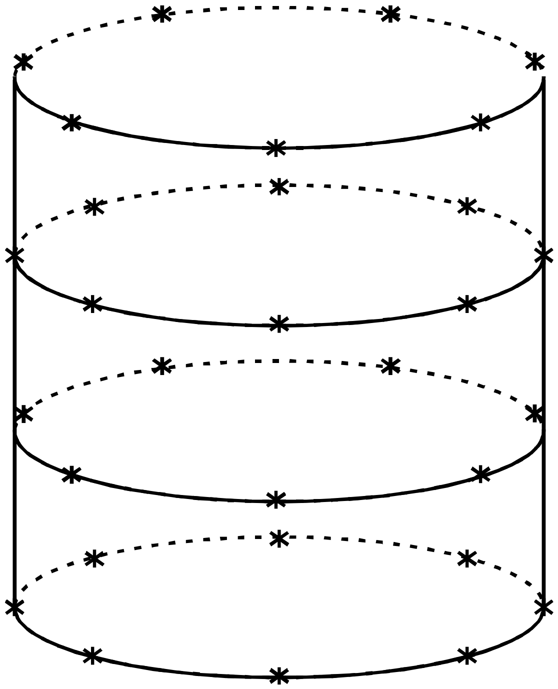


**Figure 23 A distribution of points on a cylinder**

Note: It is beneficial for the number of points to alternate between odd and even on the circles, *viz.*, in figure 23 above seven points on the first circle, eight on the second, seven on the third, *etc*. This choice will enable any lobing effect on the circular cross section to be detected.

If the straightness of the cylinder is important then more circles should be used with fewer points on each circle. If the circularity of the cross section is more important, more points on each of a smaller number of circles should be used.

If the user is probing a helix then substitute ‘circuit’ for ‘circle’ in the above paragraphs.

Note: When measuring a hole whose axis is not square with the datum plane into which it has been machined, the measurement strategy adopted by the user should be that of treating the hole as a cylinder and not simply as a circle.

If all the touch points are taken in one plane, when the data are projected onto the XY plane, the computed centre of the hole will not correspond to where the actual hole intercepts the

XY plane of the workpiece. The output data of the hole will indicate that it is elliptical in nature.

To overcome the potential for a measurement error, the hole should be probed using the method described above for a cylinder using planes parallel to the XY plane. Such probing will enable the software to compute the position at which the axis of the cylinder intersects the XY plane. The software will also compute the out-of-squareness of the hole in the XZ and YZ planes.

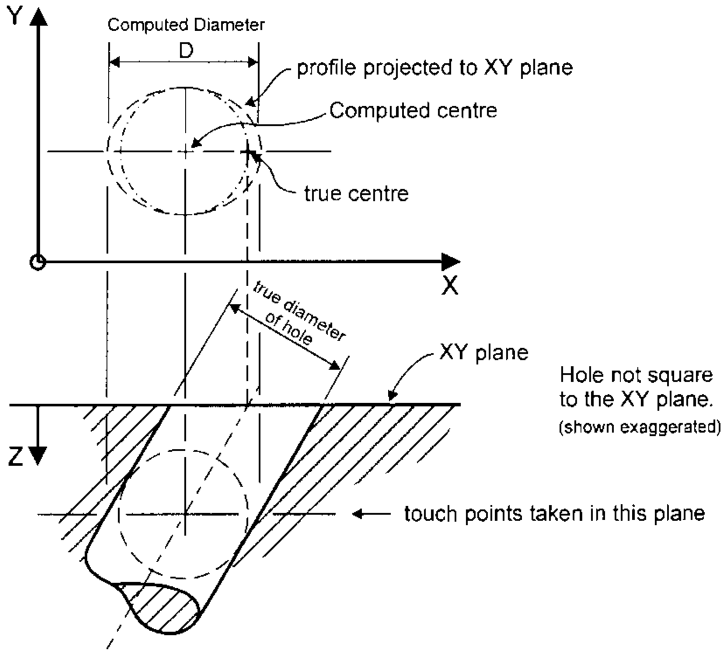



**Figure 24 Hole not square to datum plane XY (© D. R. Coleman & T. F. Waters)**

### *Cones*

A nearly uniform distribution of $N$ points on the frustum of a cone can be produced in a similar way as that on a cylinder with the target points placed on parallel circles. In the case of a cone the number of points on the circles should be chosen to decrease towards the vertex of the cone.

If the cone is of:
height $h$,
side $l$,
with radii $r_1$ and $r_2$ ($r_2 > r_1$) at its ends.

Calculate the side length $l$ using the formula $l = \sqrt{h^2 + (r_2 - r_1)^2}$

$n_c$ should be determined as an integer close to $\sqrt{\dfrac{lN}{\pi(r_2 + r_1)}}$

and $s$ is determine as an integer close to $2\pi(r_2 - r_1)/l$

For each of the $n_c$ space planes that are approximately perpendicular to the cone axis, the target points should be taken at the intersection of the plane and the cone. The number of measurements on successive planes decreases by the integer $s$ for a plane nearer the vertex of the cone

Consider for example a cone where:

$r_1 = 10$ mm,
$r_2 = 15$ mm,
$h = 20$ mm,
$N = 35$.

Using the formula $l = \sqrt{h^2 + (r_2 - r_1)^2}$ to determine the side $l$ gives.

$$l = \sqrt{20^2 + (15 - 10)^2}\ ,$$
$$l = 20.6 \text{ mm.}$$

Using the formula $\sqrt{lN/\{\pi(r_2 + r_1)\}}$ to determine $n_c$ gives

$$n_c = \sqrt{lN/\{\pi(r_2 + r_1)\}},$$
$$n_c = \sqrt{20.6 \times 35/\{\pi(10 + 15)\}},$$
$$n_c = 3.03 \qquad \textbf{choose 3}$$

Using the formula $2\pi(r_2 - r_1)/l$ to determine $s$

$$s = 2\pi(r_2 - r_1)/l\,,$$
$$s = 2\pi(15 - 10)/20.6\,,$$

$s = 1.53$ **choose 2**

Figure 25 illustrates the above example which results in 10, 12 and 14 measurements ($N$ = 36) on three circles.

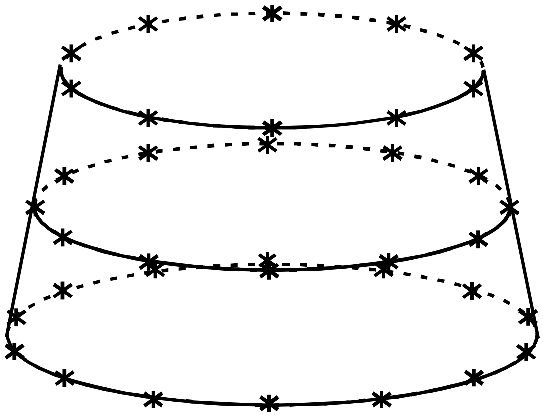


**Figure 25 A distribution of points on a cone**

If the circularity of the cone is important, use more points on the circles.

If the straightness or angle of the cone is important, use more circles.

# The scientific approach

A scientific method for choosing the distribution of points utilising prior knowledge of the component form is described in the report '*Traceability of CMM Measurements: Influence of the workpiece error on the measurement uncertainty (virtual workpiece)*' by Maurice Cox. Some of the main points of that document are highlighted below. This section may be omitted at first reading.

### *The problem*

When a real feature on an industrial part is measured with a co-ordinate measuring machine it is necessary to select a suitable probing strategy, that is to say, the number and placement of the measurement points. Once this decision has been made, the real feature is measured according to this strategy. It is a difficult task to make this decision in an objective manner, and particularly in a way that enables reliable estimates of the uncertainties of the measurement results to be made. The decision is therefore often made in an arbitrary manner. If a probing strategy (also known as a measurement strategy, measurement procedure or sampling plan) is inadequate, an associated feature fitted to the measured points can depart significantly from that which would be obtained from the use of a superior probing strategy. The consequences of an inadequate probing strategy are that the geometric parameters (diameter, angle, *etc.*) of the associated feature may differ considerably from the correct values and therefore possess large uncertainties (which cannot readily be quantified). Moreover, the estimate of the form error of the feature is almost certain to be optimistically small. In many circumstances, it is expected that the uncertainties due to the measurement strategy, as a consequence of form error, constitute the major contribution to measurement uncertainty (Hocken, Raja and Babu, 1993; Phillips, 1995; Weckenmann, Heinrichowski and Mordhurst, 1991). This point has also been forcibly made at the International Standards Organisation Committee TC/213/WG10, Coordinate Measuring Machines.

### *A solution*

It is fundamental that in the absence of any prior information about the real feature being measured it is not possible to provide a probing strategy that will ensure that the measurement results will have a specified target uncertainty (or even to quantify the uncertainty of the measurement results). However, if a particular feature, a cylinder say, is being measured routinely as part of industrial production, it will be appropriate to learn about that feature by making initially (and periodically thereafter) detailed measurements of the part. From such measurements it is possible to deduce a probing strategy that is economical for the target uncertainty and the effect of using it.

In taking detailed measurements, it is not essential that a CMM is used for this purpose, even though subsequent measurements will for production purposes be made with a CMM. Indeed, there can be advantages in using a different, special-purpose instrument such as a form or a roundness-measuring instrument. For instance, a roundness-measuring instrument can provide very detailed information about the profile of a section of a real feature that is nominally cylindrical. Measurements should, however, be taken with an instrument that is traceable and that operates to sufficient accuracy.

It is necessary that a probing strategy account for the uncertainty that results from the fact that, even for the same number of points and the same relative placement of those points, the measurement results will in general be different. As an illustration, consider the measurement and re-measurement of a cylinder, before and after repositioning (for example, a rotation about its axis). Different points on the cylinder are measured in each instance, thus sampling different regions of the surface (which contains form deviation), and consequently different measurement results will be obtained. Another such situation arises when it is necessary to decide how close to an edge of a real feature measurement should be taken.

A considerable difficulty is the reliable estimation of these uncertainties. In particular, an estimate of the maximum form deviation (MFD) of the real feature obtained from the residuals of an associated feature will almost invariably be an *underestimate*, perhaps significantly so, of the actual value, and hence be *biased*. This underestimation is a consequence of the fact that only a (usually small) finite set of points is sampled. The bias is in the *unsafe* direction, it generally being better for tolerancing purposes to determine, if possible, an *overestimate* of this important quantity. Statements can also be made about the parameters of the associated feature (and also about quantities derived from associated features, such as the distance between the centres of two associated spheres, corresponding to real features such as balls on a ball plate). The estimates obtained for a given set of measurements could be underestimates or overestimates of the values that would have been obtained from a detailed probing strategy.

Further, akin to the substitution method of measurement (ISO 15530-3), the comparison of previous detailed measurement with current "coarse" measurements provides a basis for *correcting* the measurement results and the MFD in a way that bias is reduced. Moreover, it also permits the uncertainties of these corrected values to be estimated. In particular, uncertainties associated with either uncorrected or corrected results can be obtained. To illustrate the point, the correction to the parameters and the MFD obtained using a particular probing strategy, for example, a probing strategy utilising ten uniformly-spaced measurements of a nominally circular profile, is such that the values so obtained correspond to (estimates of) those which would be obtained from a probing strategy containing a large (and for practical purposes what amounts to an *infinite*) number of uniformly-spaced measurements.

Finally, the approach provides a mechanism for designing optimal probing strategies. Thus, questions such as "What is the smallest number of measurements needed for a probing strategy utilising uniformly-spaced measurements such that the uncertainty in a particular (corrected or uncorrected) parameter is no greater than a specified amount?" can be considered.

The following assumption is made (this is expected to be a reasonable one in a range of circumstances). The production process is such that machine-tool wear results in time to gradual changes to the physical dimensions of the parts. On the other hand the nature of the form deviation (which is typically a consequence of aspects of manufacturing-machine performance other than tool wear) is such that once characterised it can be expected to be substantially valid on a longer time scale. One of the purposes of regular inspection is of course to ensure that changes to physical dimensions of a part and their effects are reliably identified, in order that necessary adjustments to the production process can be made.

The methodology and procedures developed at NPL address the above issues. They are based on the concept of a *virtual feature*. A representative manufactured part is synthesised in terms of a mathematical model from which appropriate probing strategies can be deduced. In particular, the approach provides an estimation of the uncertainties associated with any particular measurement strategy.

Guidelines for assessing measurement uncertainty due to workpiece form errors are overdue; work at NPL has made a contribution to the development of such guidelines. It is expected that they will assist in assessing the contribution to the overall uncertainty budget for the measurement of a part that arises from this consideration. Many of the other contributions, *viz.*, the uncertainties arising from the random and systematic errors of measurement, can be estimated through the concept of the Virtual CMM, which was the concern of the parent project of which this work was a part. Virtual CMMs are discussed in NPL Good Practice guide No. 130.

### *Basic principles and limitations*

It is important to appreciate that it is not possible to realise an optimal probing strategy for a complete class of features such as cylinders using any approach. An optimal probing strategy depends on a number of factors including

1. the “shape” or “aspect ratio” (for example, ratio of cylinder length to diameter),
2. whether the real feature is full (for example, a complete sphere) or partial (for example, a spherical cap),
3. accessibility to all or part of the surface of the real feature,
4. the form deviations of the real feature.

An optimal probing strategy can only apply to a particular class of closely related real features, for example, as indicated, to a sequence of nominally identical parts coming off the production line (or to a set of parts that for other reasons are expected to be nominally identical).

Assume that it is possible to take sufficient measurements on an initial part (or parts), and periodically thereafter, to enable the parts of which it is representative to be adequately characterised in terms of its form-deviation function and, consequently, its maximum form deviation. For example, although parts may normally be measured with a probing strategy containing, say, ten points, much more detailed information would be obtained by measuring every 1000$^{th}$ such part, say, at one hundred points.

This information would be used as the basis of obtaining the detailed data needed for the operation of the any method utilizing prior knowledge of the component form. It would also be valuable for quality-control purposes. It is to be noted that, in the above very simple example, only about 1 % more measurements than normal would *on average* be required. (This figure would be different in different circumstances.) However, there would be gains in terms of the quality of the quantities estimated and their uncertainties, with desirable consequences regarding the setting and meeting of manufacturing tolerances.

The approach implicitly assumes in broad terms the *constancy* or *slow* changing of the production process. However, it can also be used to assist in the *monitoring* of this aspect of production.

The report mentioned at the start of this section shows how to construct and use such a virtual feature in order to synthesise a real feature. By this means candidate probing strategies can be studied, corresponding measurement errors deduced (if required to provide corrections to measurement results) and optimal probing strategies can be designed.

## Using a typical UES package

An uncertainty estimation software (UES) package, for instance PUNDITCMM, allows probing strategies (figure 26) to be investigated based on typical form error generated by the machining process (figure 27). Based on the defined shape and the probing strategy the measurement uncertainty can be calculated (figure 28) for the defined CMM.

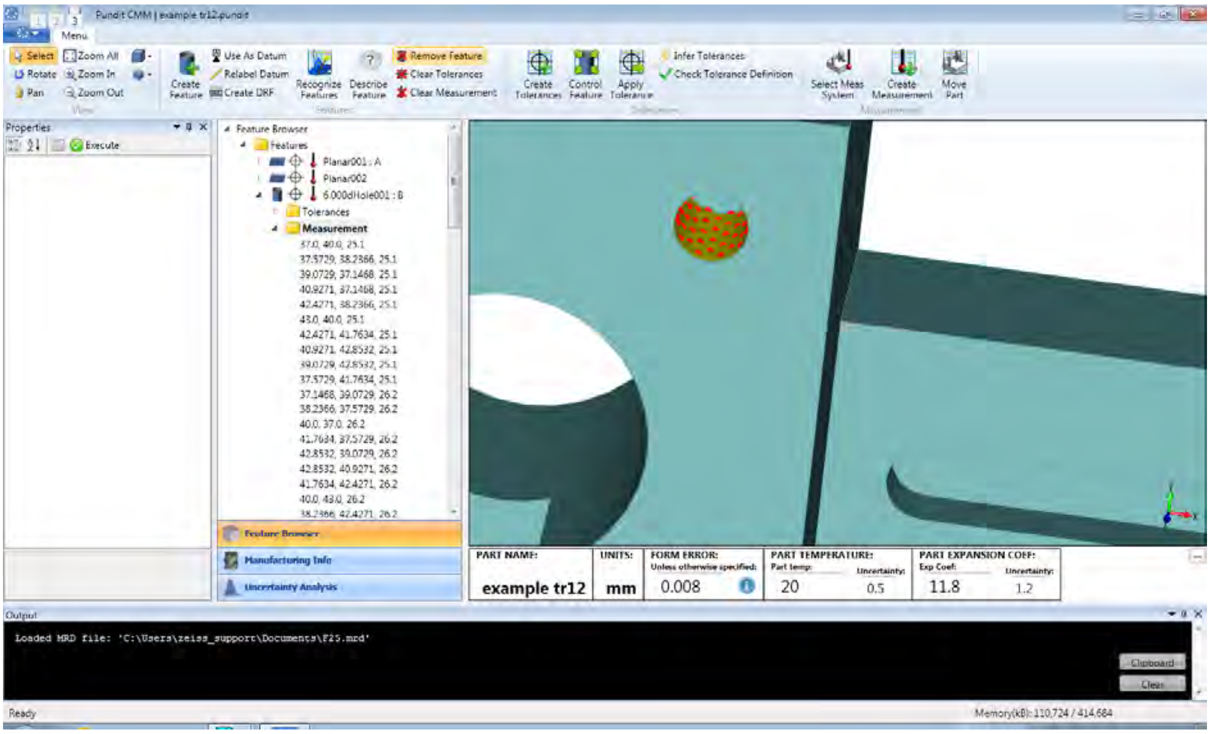



**Figure 26 Defining the probing strategy in a UES package. The red dots show the probing strategy selected with each dot representing a contact point.**

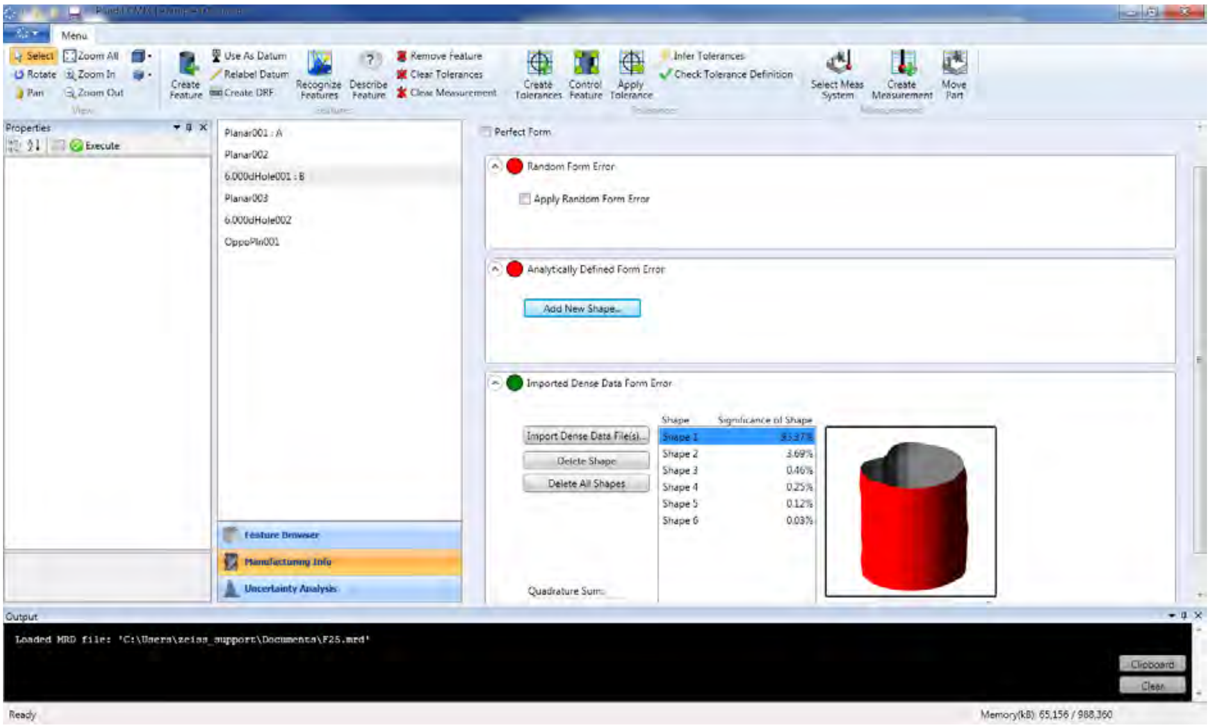



Figure 27 Using UES to define feature form error. The defined shape of this hole is shown in red.

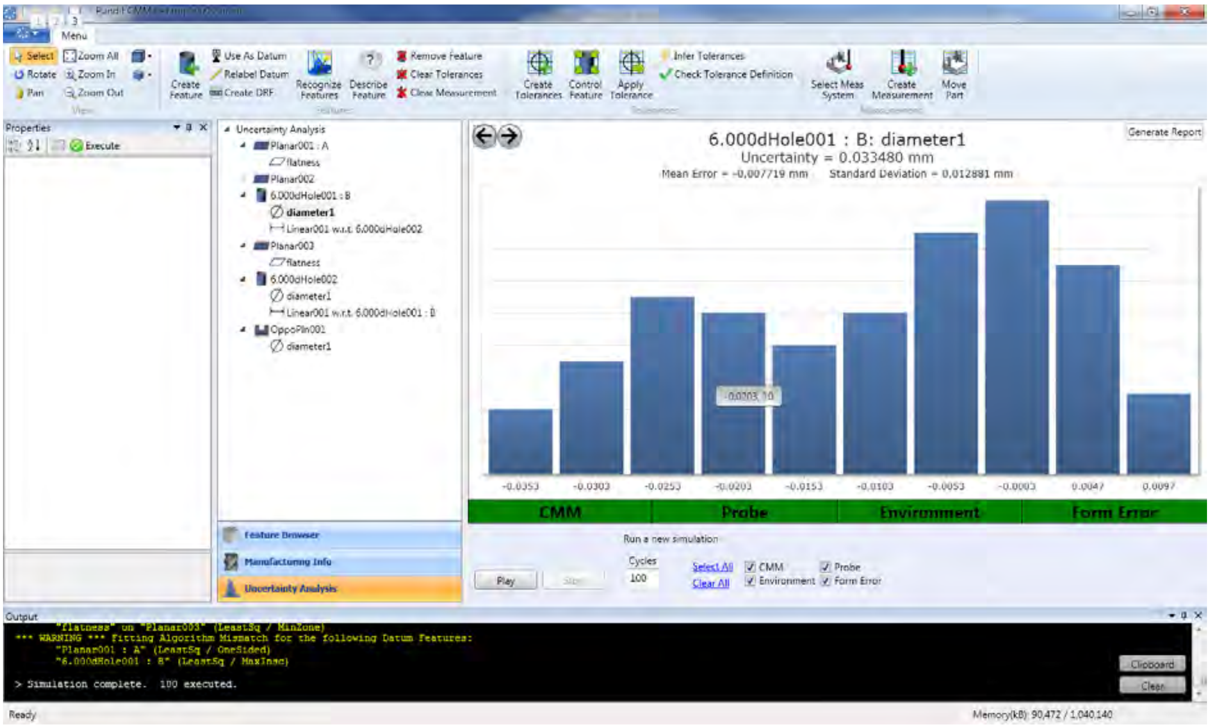



Figure 28 Assessing uncertainties based on input shape errors using UES

## Partial features and partial arcs

In general a partial feature is one that constitutes a fraction of a complete feature. Either an actual feature might be of this form, or, because of access difficulties, it might be possible to probe only part of a complete feature. Examples are an arc of a circle, a patch of a sphere and a frustum of a cone. For instance, a partial (circular) arc might represent a corner radius. Such features can be more difficult to measure than full features.

Because of the incomplete nature of the surface, errors can occur when trying to predict the centre and radius of the best-fit circle from the co-ordinate data. It is often better to fit a circle equal to the specified radius and then look at the deviations of form from this circle.

This point can be demonstrated by measuring a circular item of say 25 mm radius by contacting the surface at twenty points around the circumference. Note the centre co-ordinates and radius. Now make a measurement but this time contact at 20 points in a 45° sector of the ring. Depending on the form deviations in the surface the results could be quite different.

Consider a partial (circular) arc, measured at ten points uniformly spaced over part of a nominally circular feature, as in figure 29.

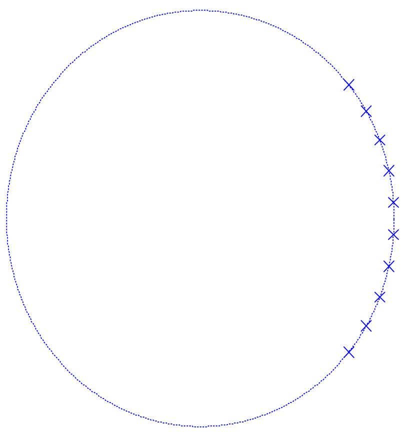


**Figure 29 Ten uniformly spaced measurements on a partial arc, showing the (nominal) circle of which it is part**

Suppose a least-squares circle is fitted to these points to obtain the radius and centre co-ordinates of the circle of which the arc is part. These circle parameters will have uncertainties associated with them as a consequence of the CMM measurement uncertainties. These uncertainties can be considerably greater when determined from such partial arc data as opposed to the use of measurements giving sensible coverage of a complete circle.

A partial arc will subtend a certain angle at the centre of the circle. Suppose the length of an arc is halved, thus halving the subtended angle. Ten uniformly spaced measurements taken as before, but over this shorter arc. The resulting uncertainty of the computed radius is increased by a factor of approximately four, with a comparable statement concerning the uncertainty of the centre co-ordinates. This result applies for circular arcs that subtend any angle up to approximately 80°.

The significance of this result can be seen by applying it to an arc subtending, say, 80°, and then one subtending, say, 5°. The uncertainty in the radius determined for the latter case is greater than that for the former by a factor of over 250.

In such extreme circumstances, it must be questioned whether the above circle parameters are appropriate for an actual measurement task. To determine the radius and centre of a partial arc to within a small uncertainty might require an accuracy of co-ordinate measurement that is not readily available. A design specification in terms of such quantities can be regarded as unreasonable. A specification that required the form deviation (departure from circularity) to meet a certain tolerance would be much more reasonable. Determining whether the measurements of the arc indicate acceptance in this sense is simpler and forms a better approach. Information is available[1] on appropriate approaches.

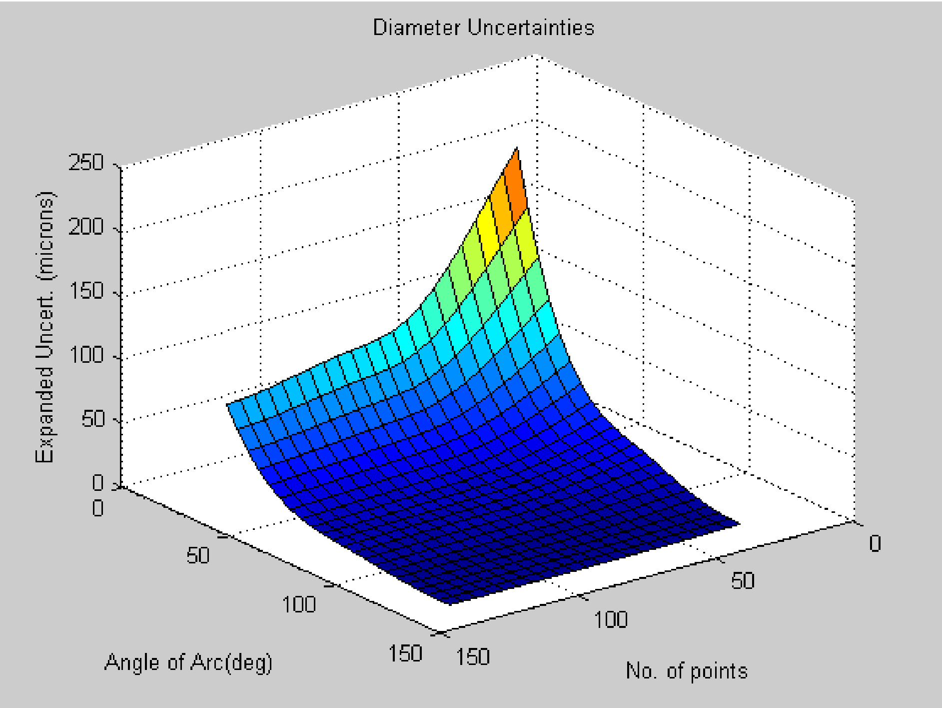



**Figure 30 Varying arc angle and number of points (Courtesy Metrosage)**

Figure 30 shows how the uncertainty in determining a hole diameter increase as the arc size reduces. Increasing the number of points on the arc helps but for small arcs the uncertainty

[1] G. T. Anthony, Helen M. Anthony, M. G. Cox, and A. B. Forbes. *The parametrization of geometric form. Technical Report EUR 13517 EN, Commission of the European Communities, Luxembourg, 1991.*

can be tens of micrometres. However, for profile, uncertainties are in the 3 to 4 micrometre range (figure 31).

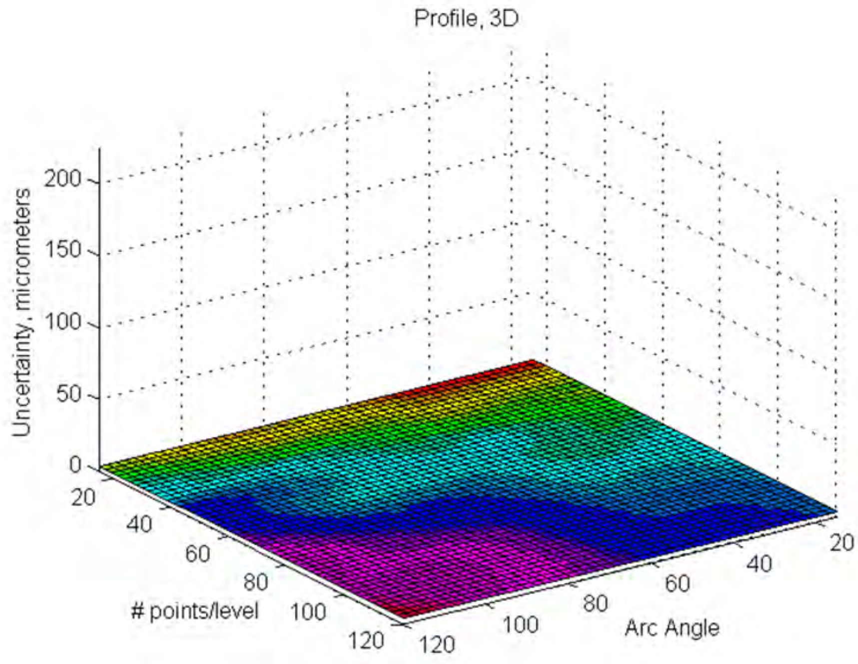



**Figure 31 Profile uncertainties (Courtesy Metrosage)**

## Chapter summary

- Take care in the selection of the number and position of probing points
- Too few points – results may be in error
- Too many points – the measurement may take too long and errors will result from drift due to changing conditions
- Be aware of the problems associated with partial features
- Use of UES in determining number of points

# Programming the CMM

# 7

**IN THIS CHAPTER**

- Programming the CMM
- The user requirement
- The functional specification
- Testing the program
- Probing considerations in the measurement Strategy
- General points to note
- Recommended details the program should contain
- Program version control

For most measurements on a CMM a program will be written to move the machine, contact the relevant surfaces, compute Gaussian associated features and then make calculations based on those features. An error in anyone of those steps can lead to errors in the final output. There is, therefore, a certain amount of good practice that needs to be followed to ensure the correctness of any program created.

## Programming the CMM

Programming a CMM at the basic level involves the use of a joystick, to instruct the machine on the route to take to manoeuvre the probe around the workpiece, to define the number and distribution of target points on each surface being measured and to define the computations to be applied to the resultant data. Increasingly this programming can be carried out off-line making use of a CAD model. The importance of programming a CMM should not be underestimated since a program that contains an error could result in incorrect measurement of hundreds of parts.

Producing a user requirement and functional specification before any programming is undertaken reduces the chance of errors.

## The user requirement

The purpose of the user requirement document is to ensure that the person requesting the measurements and the CMM programmer know exactly what is required. The user requirement may be a simple statement such as 'Measure all features on the widget as per drawing number 33333 using the datum detailed on the drawing'. If no drawing exists then a more detailed description may be needed. It is important in all cases that the target measurement uncertainty is defined. Attempting to achieve a measurement uncertainty of 0.001 mm, when 0.005 mm is all that is required does not make sense. Consideration should be given to the rules defined in ISO 14253. A form for providing a user requirement is included at Appendix C.

## The functional specification

It is good practice to plan the program in advance of developing the program code. The purpose of the functional specification is to allow the CMM programmer to plan his measurement strategy so that errors and problems can be spotted early on in the process. A functional specification also allows for the program philosophy to be checked by another operator before any coding has been done. Appendix D contains a suggested Functional Specification form.

## Testing the program

The CNC program should always be tested before it is run in earnest. Appendix E gives a suggested checklist.

One of the items is ‘check measurements against those made with a rule’. This may sound ridiculous but many errors in programming a CMM may produce results that are wrong by millimetres, for example, by an amount equal to the probe radius.

It is good practice to undertake a more thorough testing of a CMM program by measuring a component with the program and by using more traditional techniques and instruments such as using micrometers, callipers, height gauges, *etc*. However, check that any differences are not just due to the different measurement methods used.

## Probing considerations in the measurement Strategy

The performance characteristics of any probing system are influenced by the measurement strategy selected by the user. For example, the machine dynamic errors depend on factors such as probing direction, probe speed, approach distance and acceleration values. The effect of various probing parameters on the accuracy of a CMM fitted with a touch trigger probe was investigated and reported in *Some performance characteristics of a multi axis touch trigger probe* by F M M Chan *et al.* (1997). Further information on this investigation can be found in the NPL ‘CMM Probing’ Good Practice Guide, No. 43.

## General points to note

Many software packages contain an automatic feature measurement function that allows the CMM to automatically move to a defined feature and take measurement points on it facilitating the creation of a Direct Computer Controlled (DCC) CMM program. In such a system, the user defines the geometric feature by keying in its nominal geometric information or by indicating the feature on a CAD model.

To obtain the most efficient use of the DCC CMM, particularly in high volume production situations, use the CMM for part inspections as much as possible. Write programs off-line using a CAD model. Ideally, a facility should exist for the program to be imported from an offline workstation into the CMM and run with little or no editing.

The use of a DCC program improves reproducibility of measurements. The use of loops to measure the artefact more than once should be used and mean values calculated. Consider using conditional loops that allow a feature remeasurement should form deviations be larger than a set value. The downside of using a CNC program is that the machine makes contact with exactly the same points each time potentially missing deviations in form that lie between points.

The user requirement, functional specification and testing forms mention earlier are purely an aid to planning a CMM program. What is important, however, is that a mechanism for recording the information contained in the forms is available within the organisation.

It is good practice to keep records of all CNC programs and to make backup copies. Keep a revision history that records the version number of the CNC program, details of any modifications made to it and who made the modifications. The version number should always appear on the printout from the program.

The key reason for this record is that it provides evidence of traceability. It should be possible from the printout of the measurement of any component to be able to determine at the very least:

- the version of the CNC/DCC program used to make the measurements;
- the operator;
- the programmer; and
- the date and time.

It is good practice to write programs for maintainability and programs should contain comments. Feature names and characteristic names should be sensible. Do not use the default Circle1, Plane 1 *etc*.

## Recommended details the program should contain

It is good practice that all programs should contain the following information.

- Program name.
- Program version.
- Date written.
- Version history with description of changes.
- If appropriate copyright notice.
- Name of author.
- Details of the component the program measures.
- Any drawing numbers.
- Reference to any CAD files.
- Brief description of the program purpose/function.
- Details of any holding fixtures (imbed photo).
- Instructions on how to set the component on the CMM.
- Instructions/photo on how to set up the CMM probing system.

Programs should have sufficient comments to explain the logic particularly for conditional tests and calculations. The program name and version number shall be included in the results output.

## Program version control

All programs must be subject to version control. Reflect modification of a program in the version number.

Examples of minor changes, which do not require a version number change, are

- tidying code to remove redundant lines; and

- changes to improve maintainability, for instance, adding more comments.

Examples of major changes, which do require a version number change, are

- change of a tolerance;
- change of a nominal size; and
- adding an extra measurement or calculation.

## Formatting records

It is important when making any measurements that full records are kept either printed or electronic. If any problems occur in the future it is easier to trace a measurement record from the job details.

The user should ensure that an accurate record of the assessment software output is available. This record normally has two parts - essential and optional as defined in BS 7172. However, the user should add to this information details of the measurement strategy, for example, probe, stylus, extensions used, calibration artefact used to qualify the stylus, number of points used and a brief description of the set up and direction of approach of the probe.
BS 7172:1989 details the following:

- Essential information (should always be provided)

    - Nature of assessment.
    - Identification of the workpiece (for example, serial number, type.)
    - Details of the assessment (parameters of reference, departure from form *etc*.)

- Optional information

    - Job title.
    - Place, date and time.
    - Environmental details.
    - User.
    - Any other information considered relevant.

Keeping records of this nature will provide the user with historical data that can be used to reproduce a particular measurement scenario but more importantly will also establish a knowledge base containing CMM inspecting experience that can be used for the development of future measurement strategies.

## Chapter summary

The contents of this chapter can be summarised as follows:

- plan the CNC program;
- check the CNC program;
- test the CNC program;
- verify by another means;
- write for maintainability;
- keep proper records; and
- manage programs with version control.

# CMM Data Assessment software

# 8

**IN THIS CHAPTER**

- CMM data assessment software

This chapter will consider the importance of selecting the most appropriate fitting routine.

## CMM data assessment software

The data points that are recorded during the probing operation may contain two types of error that is to say form deviation and measurement errors. These two errors can lead to errors in assessment by the software.

Form deviation occurs in the workpiece itself and arises from generally repeatable aspects of the manufacturing-machine performance such as machine tool elasticity and workpiece fixturing. Consider, for example, data obtained by measuring a number of points on a nominal circle on a workpiece. From the data gathered the software assessment would determine an associated feature in the form of a best fitting mathematical circle and compare its parameters with the corresponding values from the drawing. However if the circle were to be measured using a different set of points form deviations would almost certainly result in a different best fitting curve or surface.

Measurement error is on the other hand due to the inability of the co-ordinate-measuring machine to provide exact values of the co-ordinates of points on the workpiece.

In practice the measured data can have errors that are either predominantly form deviation or predominantly measurement error or it may contain errors of comparable size from both sources. The way in which the software assessment of the data is undertaken should take this into account.

Mathematical routines based on the principle of the least squares (Gaussian) method assume that deviations from the nominal have a normal distribution. The result obtained is the average size of the feature. However, if the feature has significant departures from the assumed nominal form the average size will be a misleading result. The alternative method of analysis is based on the enveloping sizes method (Tchebyshev method).

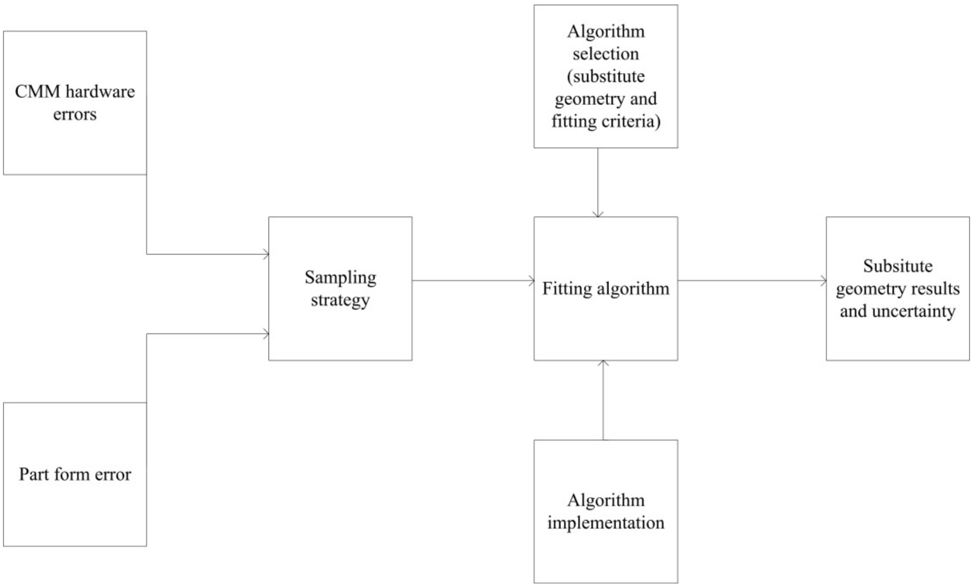



**Figure 32 The factors effecting a CMM measurement (adapted from Coordinate Measuring Machines and Systems)**

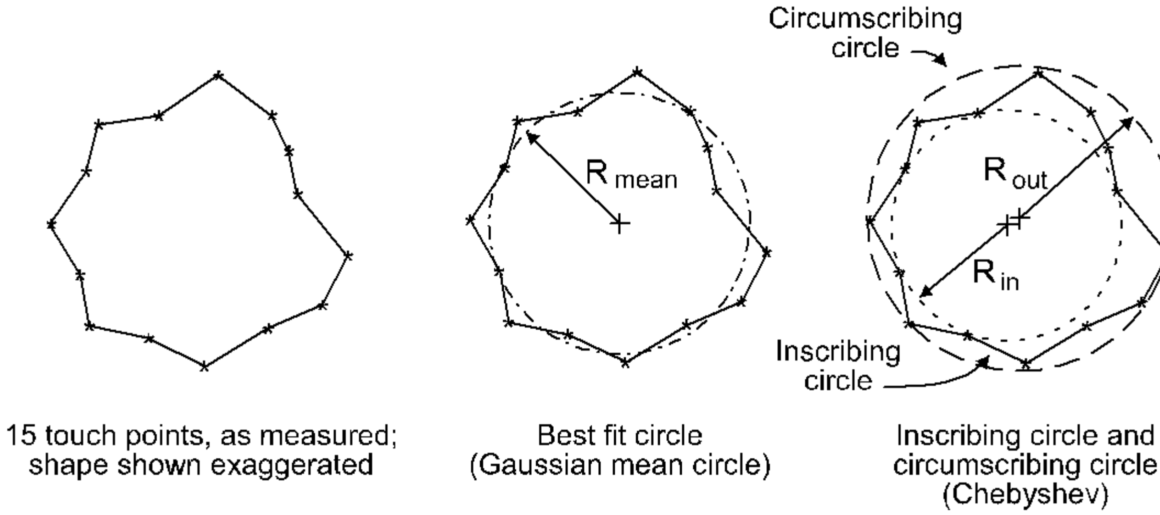



**Figure 33 Average size (Gaussian) and enveloping sizes (Chebyshev)(© D. R. Coleman & T. F. Waters)**

For example, if the measurement strategy used provides for a measuring accuracy that is significantly greater than the accuracy of the machining process used to manufacture the workpiece, the measurements can be taken as accurate information about the form of the component. In this, case software assessment methods should be based on the largest inscribed, smallest circumscribed or minimum zone forms.

However, if the opposite applies, that is to say, the machining process accuracy is considered to have much greater accuracy than the measuring accuracy, much of the form data will be obscured by the measurement error. In this case, least squares analysis of the data is recommended.

Software routines based on the Gaussian method give fast and consistent results whilst routines based on the Tchebyshev method require advanced mathematical algorithms and take longer to complete the analysis. For situations between these extremes, BS 7172: 1989 recommends that a combination of the least squares and other approaches be used. The standard does not advocate a single approach to the analysis of data but urges the use of methods that are appropriate to the task in hand.

Any software that carries out geometric form assessment should, in addition to the required numerical output, provide the user with information on the method of analysis used and a graphical output where possible. The output of a graphical record can often allow errors resulting say from dirt on the component surface to be picked up quickly.

When evaluating GPS most CMM software will pick the appropriate fitting routine in accordance with the standards. However, the user should be aware of the different situations where various fits might be used. For example to determine form, use a minimum zone fit. In general, to determine size or concentricity use a least squares fit. However, when the feature is required to mate with another feature use an incsribing or circumscribing.

## Data filtering effects

When reporting roundness the result is usually expressed with an associated filter setting. It is good practice to refer to BS EN ISO 12181-2:2011 regarding the relationship between the filter and the minimum number of sampling points. This standard also gives recommendations for the ratio between the feature size and stylus tip radius. For more information, see table 1 of BS EN ISO 12181-2:2011.

ISO 17280 gives similar advice for straightness measurement. Here the relationship between point spacing and cut-off wavelength is defined.

## Chapter summary

- Be aware of data filtering effects.

- Take care when selecting the most appropriate fit to the data.

# Software functionality

# 9

**IN THIS CHAPTER**

- Non-conventional part alignment
- The CAD interface
- Graphical feature analysis
- Automatic feature measurement
- Reverse engineering
- Offline programming
- Programming language
- Unknown geometry scanning
- Geometric tolerancing
- Complex surface measuring
- Integrated best fit
- Integrated statistics
- Uncertainty evaluating software

The wide variety of CMM software available makes it impossible for this guide to give advice on how to use the packages supplied with each and every machine. This section therefore gives a general description of what is available and the functionality the user can expect find.

CMM software has been developed and refined so that in general computer programming knowledge is seldom required to run even the most sophisticated programs. The software is usually intuitive, user-friendly and generally has a graphical interface that greatly simplifies its interaction with CAD routines. Facilities such as reverse engineering, reporting and editing tasks, provide the user with a wide set of capabilities for many demanding applications.

The software normally consists of off-the-shelf, menu-driven programs and the user is provided with a comprehensive array of help screens. Software routines are mostly easy to use and can be customised to fit individual applications without having to use a specific programming language.

The high level of compatibility of the software makes it easy to link CMMs and CAD systems to create programs directly from the CAD data. Information can be imported as either a wire frame solid or surface representation of the workpiece to be measured. CMM software can also include automatic feature measurement from CAD data, best-fit alignment, reverse engineering and 2D best-fit and 3D surfacing.

The interface between user and machine will often provide point-and-click measurement, an interactive graphic display, alignment routines, both on- and off-line programming capabilities, probe position display, and easy-to-read graphical form analysis.

The CMM's overall measurement capabilities and ease of use depend almost entirely on the inspection software provided with the machine. **The user should be aware of the functionality offered by the software and aim to use it to its full capacity.**

In summary, the following features should be available:

- non-conventional part alignment;
- CAD interface;
- graphical feature analysis;
- automatic feature measurement;
- reverse engineering;
- offline programming;
- programming language;
- unknown geometry scanning;
- geometric tolerancing;
- complex surface measurement;
- integrated best fit;
- integrated statistics; and
- uncertainty evaluating software.

These features are briefly explained in the following sections of this chapter.

## Non-conventional part alignment

Most CMMs provide the ability to align planes, lines and points. But applications that have offset datum planes or datum target points on complex surfaces are more difficult to set up. Non-conventional part alignment software provides the facility to set up such complex measuring applications.

## The CAD interface

CMM software may have the facility to accommodate multiple CAD file types and may also present CAD information in a clear and understandable manner on the screen (figure 34). It should allow the user to control the graphical representation (wire frame, surface and solid models) and to group and hide features for visual clarity.

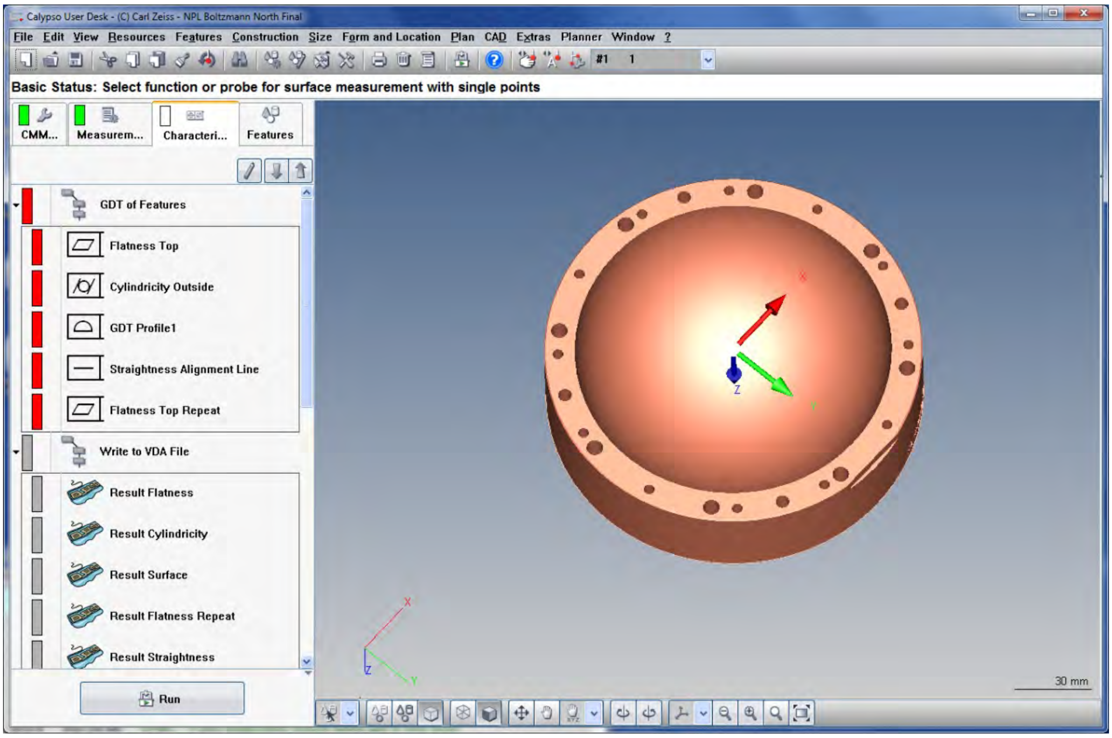



**Figure 34 A typical CAD based CMM software package**

**NOTE**

CMM software can import CAD models in both native format and in other formats such as STEP and IGES. Often the original CAD model needs to be converted to a format the CMM software can use and this conversion can lead to errors. Further conversion may also be needed between the imported format and the native format of the CMM software's CAD kernel.

## Graphical feature analysis

This software feature enables the user to evaluate the workpiece’s entire dimensional condition allowing comparison of the touch points to the known CAD definition in memory (figure 35). Good practice in this area, for instance the finite probe–tip radius problem, is considered beyond the scope of this guide but may form a topic for future guides. The essence of the problem is that with a finite tip radius the recorded tip centre location needs to be corrected in the appropriate direction to determine the co-ordinates of the contact point. If the direction of the surface normal is poorly known the correction direction will be poorly known and the correction will be made in the wrong direction resulting in co-ordinates that are in error.

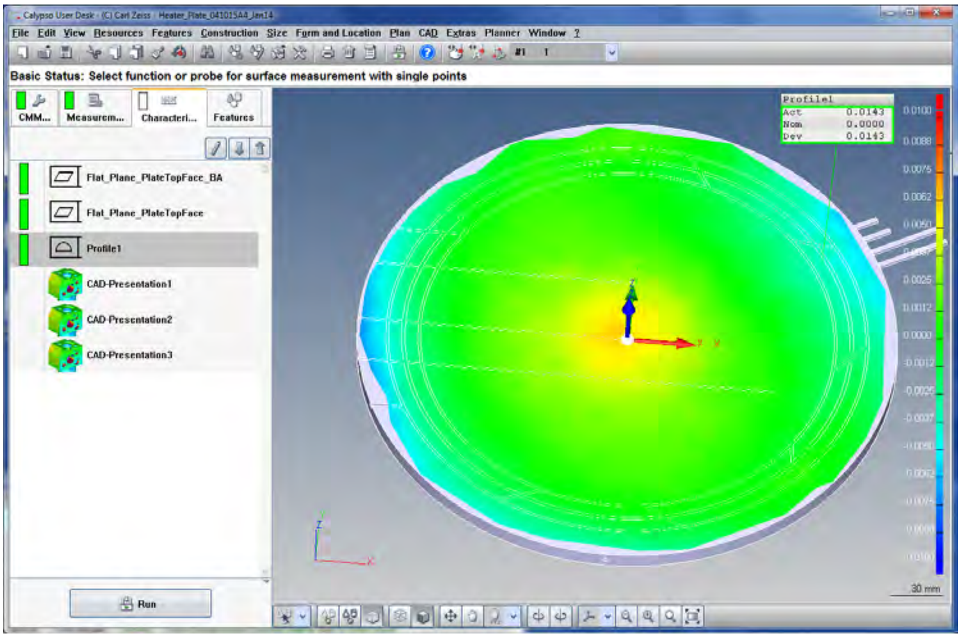



**Figure 35 Comparison of measured points with nominal CAD data.**

## Automatic feature measurement

This software facility can provide programming for Direct Computer Controlled (DCC) CMMs. The CMM automatically moves to a defined feature and takes measurement points on it. The user defines the geometric feature by inputting the nominal information or by indicating the feature on the CAD model (figure 36). Without this facility, the user would need to program manually the probe motion and the measurement points by use of the joystick only.

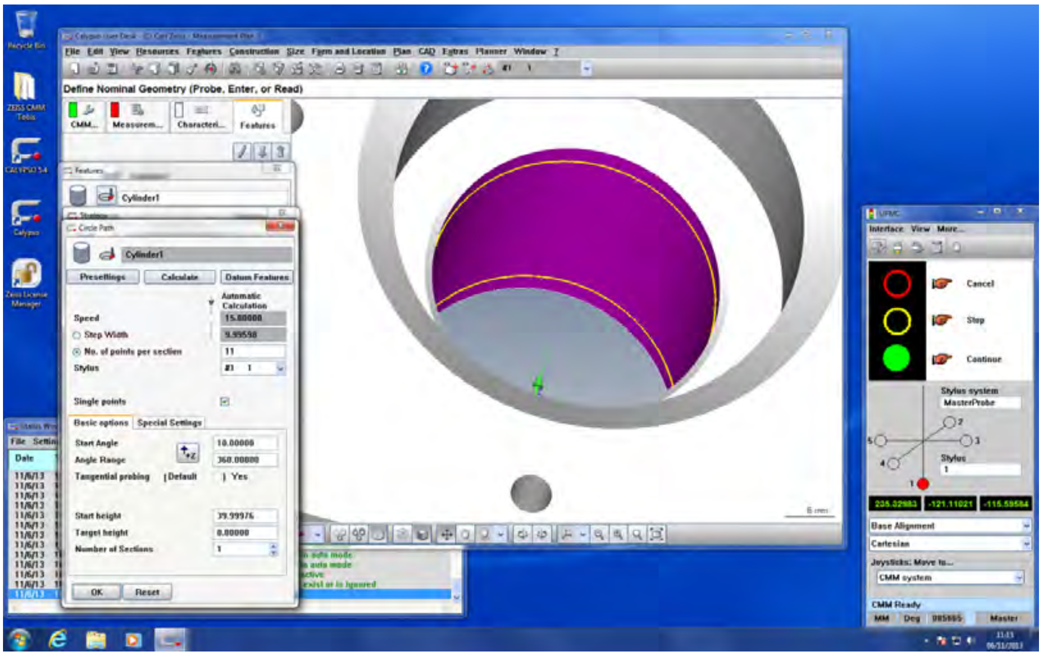



**Figure 36 Graphic based programming of a feature**

## Reverse engineering

Reverse engineering is the process of collecting data from a part and using that data to create a CAD model of the part.

Using an Initial Graphics Exchange Specification (IGES) the CMM software may be able to export measured data of an unknown or modified workpiece into a file format that can be read by a CAD system to enable a CAD definition of the workpiece to be created.

IGES is a set of protocols for the transfer and display of graphical information on remote devices *via* a computer communications network. IGES does not define any new graphical file formats, but instead uses existing formats (such as Computer Graphics Metafile) to encapsulate graphical data.

## Offline programming

To maximise the throughput from a DCC CMM, particularly in high production operations, the machine should be used as efficiently and effectively as possible. In order to avoid downtime when developing a measurement program it is essential that off-line programming be utilised.

Offline programming software allows the user to write CMM measurement programs, using CAD data, without interfering with the current measuring activities of the CMM. The facility to download the program from an off-line workstation into the CMM and run with the minimum of editing is an essential feature. Offline programming software may also be able to simulate CMM paths to check for collisions *etc*.

## Programming language

The CMM industry has its own industry standard inspection software language called the Dimensional Measuring Interface Standard (DMIS) developed by the Dimensional Metrology Standards Consortium (website: www.dmisstandards.org). The use of this standard software will allow interchangeability of part programs between different manufacturer's brands of DMIS-software. Some companies also use their own proprietary languages that allow powerful yet easy-to-read programs to be developed.

The Dimensional Metrology Standards Consortium was also involved in the development of QIF and the American National Standards Institute (ANSI) has approved QIF v1.0 (Quality Information Framework, version 1.0) as an ANSI standard. QIF V1.0 provides a standardized way for defining and exchanging measurement scope (for example, bill of characteristics), measurement plans, and measurement results.

## Unknown geometry scanning

This aspect of the CMM software offers the ability to scan complex features for data without knowledge of its nominal definition. Generally, the user will indicate the start point and end point of the surface and specify the scanning density. The CMM will scan between the points gathering knowledge of the shape of the feature of surface. Good practice in this area is considered beyond the scope of this guide but may form a topic for future guides.

## Geometric tolerancing

All fundamental types of geometric tolerancing will probably be included in the software, including line and surface profile (figure 35).

It will normally be necessary to consider the uncertainty of measurement when ascertaining compliance (or non-compliance) with a drawing or specification. If no other rules exist, it is necessary to refer to ISO 14253-1 *Geometrical product specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Part 1: Decision rules for proving conformity or nonconformity with specifications*. Methods for calculating task-specific uncertainties for co-ordinate measuring machines are covered in NPL Good Practice guide No. 130.

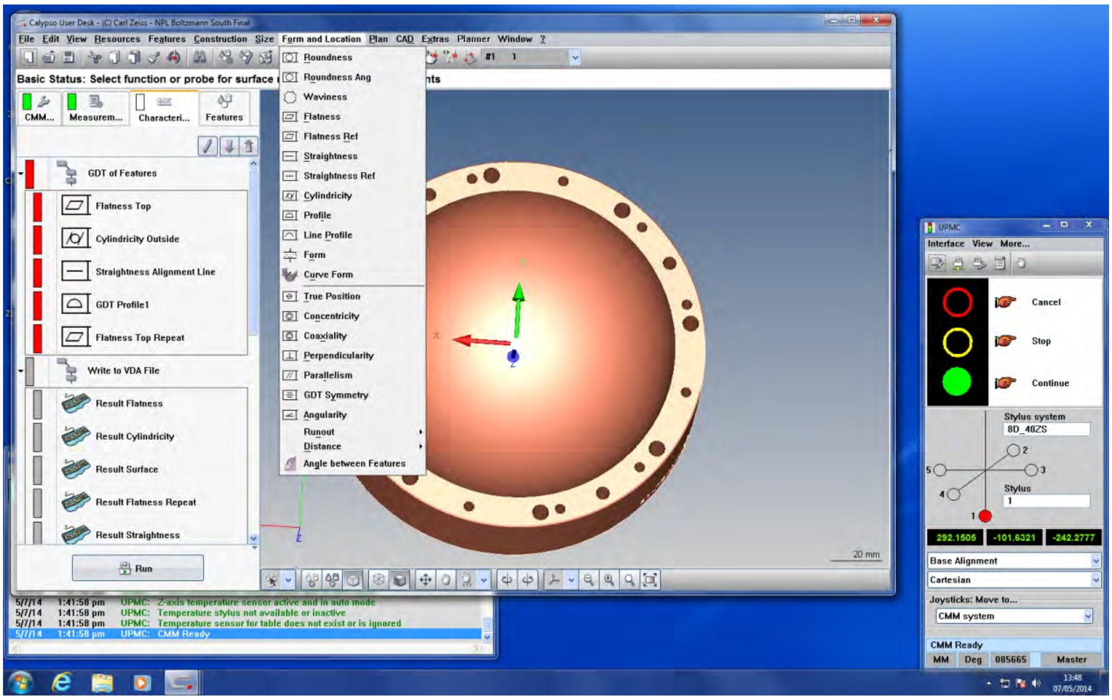



**Figure 37 Selecting geometric tolerances from within the CMM software**

## Complex surface measuring

The complexity of steps required for the alignment procedures for aerofoils, turbine blades and other similar complex shaped products provides the user with a difficult challenge. CMM software can provide the means to collect data on these complex products using a CAD surface model of the part and should also allow the user to create section lines on the surface to aid measurement.

## Integrated best fit routines

Best fitting mathematically rotates and translates the part to a position that determines whether the features as measured satisfy the design tolerances. This allows line and surface profiles to be checked without a datum reference. The user can specify any combination of features for inclusion in the best fit, enabling the results to be referred to any Cartesian or Polar axis system. The software will allow the user to evaluate the entire manufacturing process. Best fitting generally comes as third party software on an off-line system, however integration into the CMM software improves the machine’s capabilities.

## Integrated statistics

The ability to integrate statistical calculations into the inspection software eliminates the need to transfer data into third-party software and enables statistical information to be included in the assessment information record.

## Uncertainty evaluating software

Some CMM software packages have optional uncertainty evaluating software (UES). NPL Good Practice Guide 130 covers UES in more detail. Figure 38 shows a modern CMM software package with integrated UES.

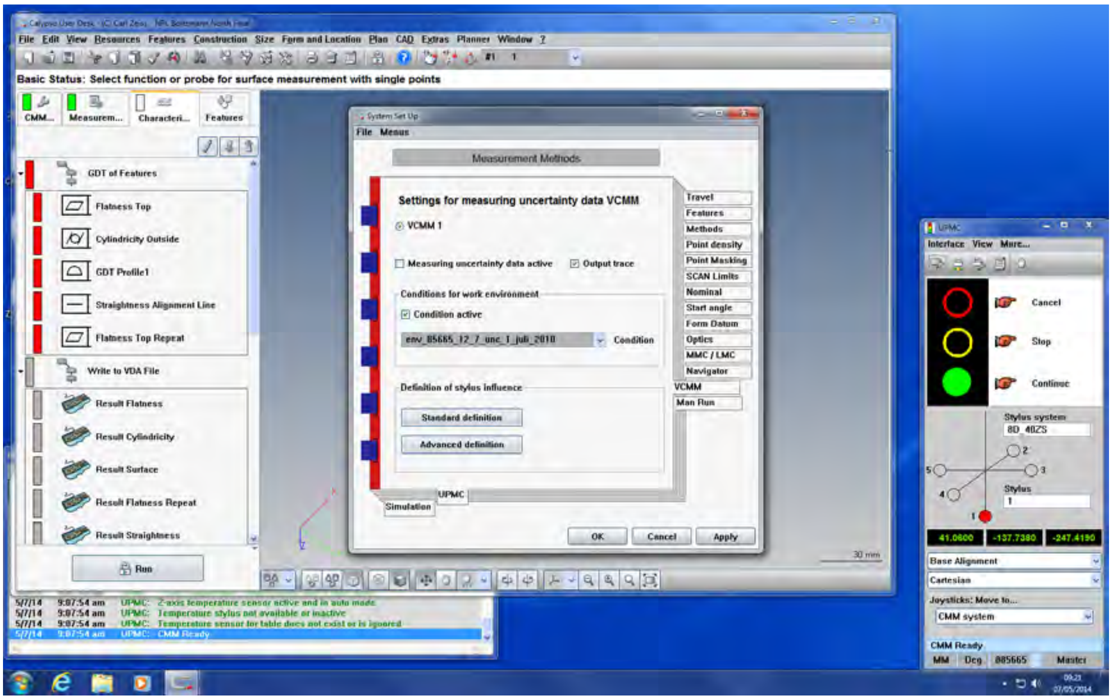



**Figure 38 CMM software with integrated UES**

UES software can be used to investigate the effect of various point distributions on the uncertainty of measurement. methods for calculating task-specific uncertainties for co-ordinate measuring machines are covered in NPL Good Practice guide No. 130.

## Chapter summary

- Be aware of all the facilities offered by your CMM software package even if you may not use those features regularly
- Know the benefits of off-line programming.
- Know how uncertainty estimating software can benefit the choice of number and distribution of points.

# Alignment criteria for standard features

# 10

**IN THIS CHAPTER**

- Length measurement
- Diameter and position of a hole
- Diameter and position of a shaft
- An angle between two lines

This chapter describes the alignment criteria for some common measurement tasks. The importance of choosing the correct alignment should not be underestimated. The term alignment describes the process of assigning a co-ordinate system to the workpiece.

## Length measurement

The establishment of a datum for a workpiece in the form of a cylindrical shaft with planar ends nominally orthogonal to its axis, for which a measurement of length is required, can be performed in a number of ways.

The datum system can be established by sampling a minimum of five points along and around the surface of the shaft. Using the Cartesian co-ordinate system the axis of the cylinder is at the intercept of the XY and XZ planes. A further additional point is required to define the YZ plane. The origin ($x = 0$, $y = 0$ and $z = 0$) is then set as shown in figure 39.

One contact point at each end of the shaft is sufficient to determine its length. The software will project the contact points onto the XY plane and surface algorithms and software calculations will determine the length distance. In the case of a slot cut in the shaft parallel to the axis of the shaft, the procedure to measure the length of the slot is the same as that for the length of the shaft.

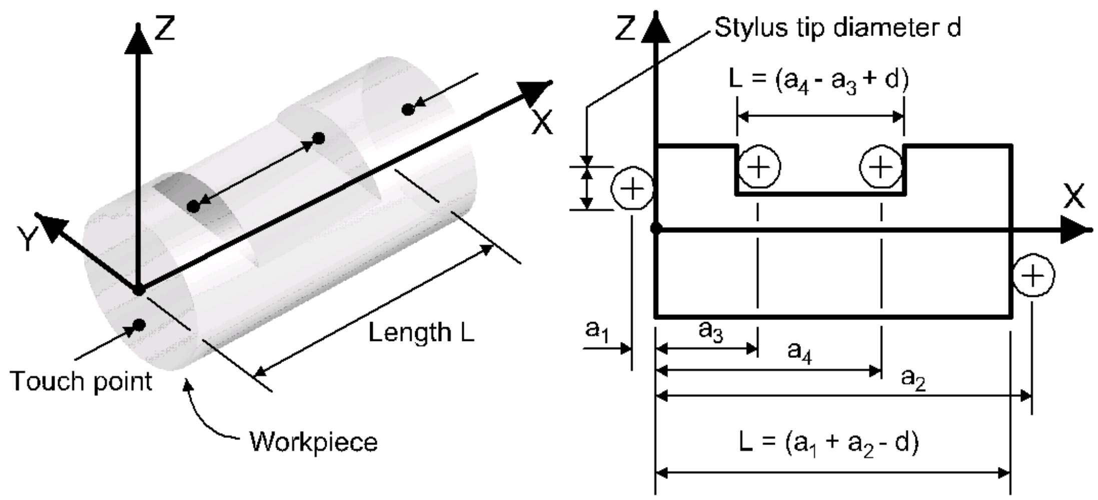
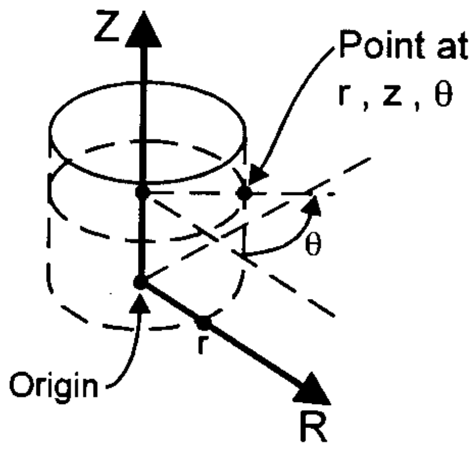



**Figure 39 Two probing points for measuring a length (© D. R. Coleman & T. F. Waters)**

A second method is to define a cylindrical polar co-ordinate system; in this case the three-axis system will consist of two linear axes and one rotational axis. The Z-axis becomes the axis of rotation and is perpendicular to the second linear axis. Once defined the shaft can be sampled at either end and the distance calculated.




*Cylindrical polar coordinate system.*

**Figure 40 Cylindrical polar coordinate system (© D. R. Coleman & T. F. Waters)**

A third method is to define the datum system by taking a minimum of three touch points on one end of the shaft in order to define the YZ plane. Two points are taken along the surface of the shaft to define the XZ plane and a further point on the cylindrical surface of the shaft to complete the datum system. Once defined the shaft can be sampled at either end and the distance calculated.

## Diameter and position of a hole

In this case, the workpiece is a simple prismatic part with a cylindrical hole at right angles to the XY plane (figure 41). The diameter of the hole and the position of the centre line of the hole relative to the origin are to be determined.

To define a datum system for a rectangular workpiece that has its origin in one corner requires six contact points. Three points are required to define a flat surface or plane (the XY plane), a further two points are required to define a line which lies on the XZ plane and a final point defines the YX plane.

The three planes are mutually perpendicular and the point of intersection of these three planes is the origin of the system, *viz.*, $x = 0$, $y = 0$ and $z = 0$.

Having established the datum the next part of the strategy is to probe the hole; the determination of the number and position of touch points to use can be calculated from the section “Distribution of points” in the guide. In this example the user is not concerned with the hole depth, so the object can be treated as two-dimensional.

In two-dimensional measurement, the co-ordinates of the touch points are projected onto the XY plane. The point co-ordinates are then used by the software to calculate the three unknowns (hole diameter and distance of the hole centre line in the X and Y plane from the origin).

An important point is that the hole diameter is determined by adding the diameter of the stylus tip; this is always the case when probing a hole, the diameter of the stylus is always subtracted when measuring a shaft. The user, by direct input, indicates whether an internal or external circle is being measured although some systems have automatic feature recognition. Some systems can distinguish between these features by sensing whether the probe moves away from the centre line after probing, in the case of a shaft, or towards the centre line after probing as in the case of a hole.

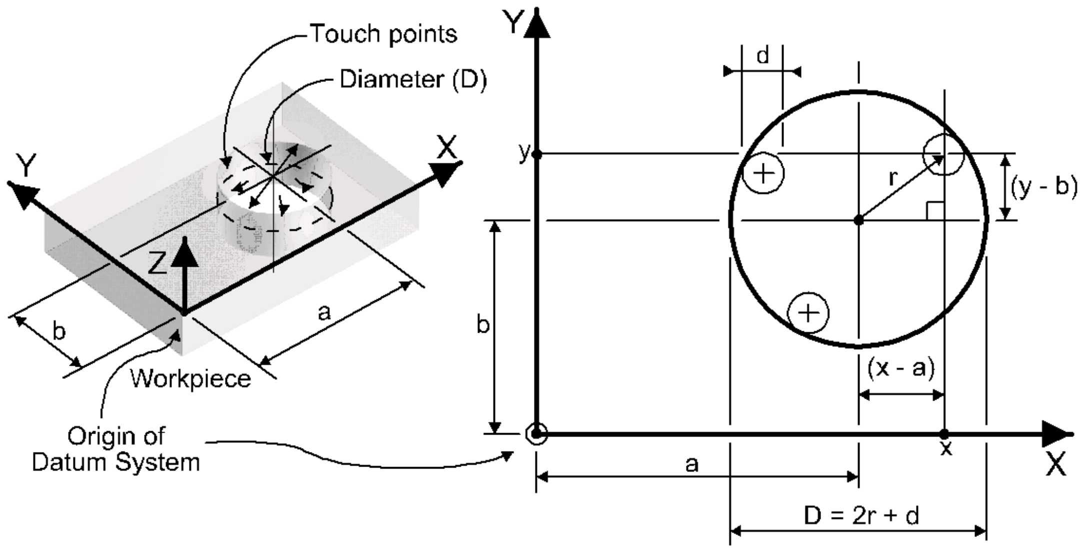



**Figure 41 Three probing points for measuring hole diameter (© D. R. Coleman & T. F. Waters)**

The user should be aware that the measurement strategy adopted in this case is two–dimensional only. It the hole was not perpendicular to the XY plane then the result would be incorrect. To obtain confidence in the result it is necessary to establish whether the hole is perpendicular to the XY plane. The hole should, therefore, be sampled in accordance with section on *Cylinders*.

## Diameter and position of a shaft

In this case the workpiece is a simple prismatic part with a cylindrical shaft at right angles to the XY plane (figure 42). The diameter of the shaft and the position of the centre line of the shaft to the origin are to be determined.

As described in section *Diameter and position of a hole* the definition of a datum system for a rectangular workpiece that has its origin in one corner requires six touch points. Having established the datum the next part of the strategy is to probe the shaft; the determination of the number and position of touch points to use can be calculated from section *Circles* in the guide. In this example the user is not concerned with the height of the shaft, so the object can be treated as a two-dimensional problem when choosing the measurement strategy.

In two-dimensional measurement, the co-ordinates of the touch points are projected onto the XY plane. The co-ordinates are then used by the software to calculate the three unknowns (shaft diameter and distance of the shaft centre line in the X and Y plane from the origin).

An important point is that the shaft diameter is determined by subtracting the diameter of the stylus tip, this is always the case when probing a shaft. The user, by direct input, indicates whether a hole or shaft is being measured. Some systems can distinguish between these features by sensing whether the probe moves away from the centre line after probing, in the case of a shaft, or towards the centre line after probing as in the case of a hole.

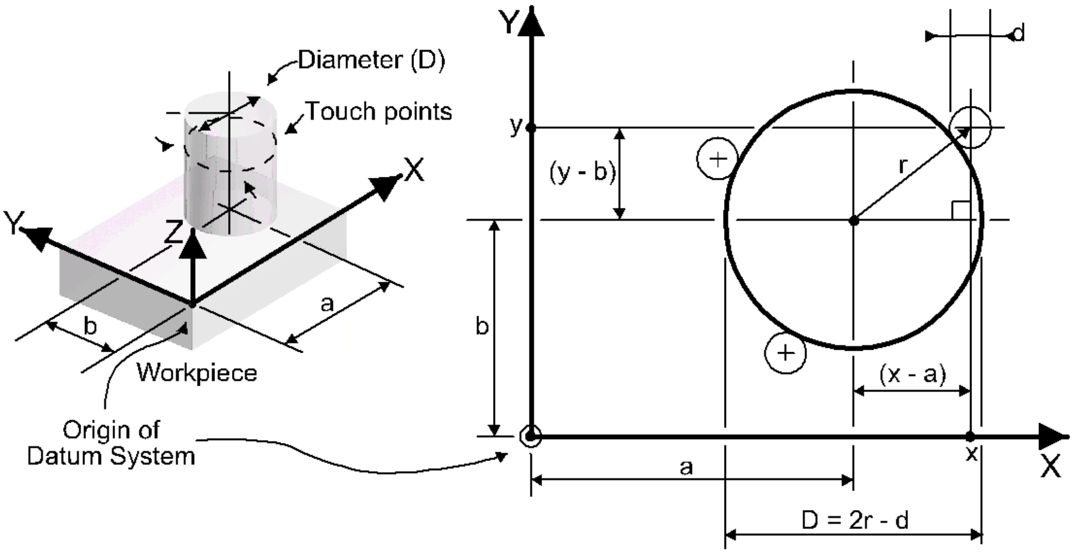



**Figure 42 Three points for measuring shaft diameter (© D. R. Coleman & T. F. Waters)**

The user should be aware that the measurement strategy adopted in this case is two–dimensional only. It the shaft was not perpendicular to the XY plane then the result would be incorrect. To obtain confidence in the result it is necessary to establish whether the shaft is perpendicular to the XY plane. The hole should, therefore, be sampled in accordance with section on *Cylinders*.

## An angle between two lines

The workpiece is a simple prismatic part with one corner cut away at an angle to the side faces.

As described in section *Diameter and position of a hole* the definition of a datum system for a rectangular workpiece that has its origin in one corner requires six touch points. Having established the datum the next part of the strategy is to probe the angled faces. This probing is carried out by taking touch points on each face in order to define two lines. The determination of the number and position of touch points to use can be calculated from section *Lines* in the guide.

The software will compute the angle and normally provides the user with two angles, one being the complement of the other; a decision will have to be taken as to which answer the correct one is based on knowledge of the software.

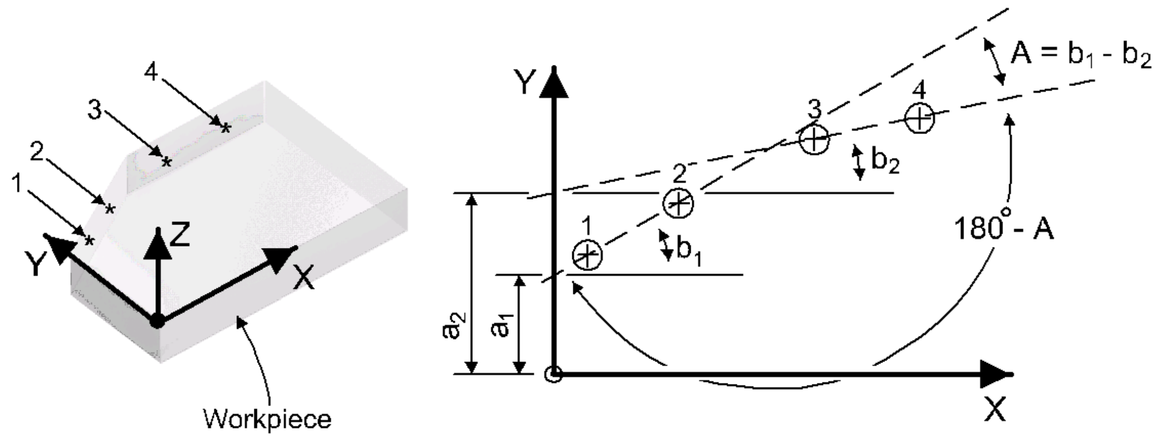



**Figure 43 Four probing points for simple angle measurement (© D. R. Coleman & T. F. Waters)**

## Chapter summary

- Be aware of the basic alignment strategies for simple prismatic parts.

# Environmental Conditions

# 11

**IN THIS CHAPTER**

- Temperature effects
- The effect of vibration
- Dust and cleanliness
- Chapter summary

The main environmental conditions that affect the CMM's accuracy and durability are temperature, vibration and dust. For a CMM to be successfully used in a production line it must be capable of operating to the required degree of accuracy in the environmental conditions in which it is situated,

## Temperature effects

The most significant factor that affects accuracy is temperature variation. Temperature variations cause dimensional changes in both the workpiece and the CMM itself. An ideal CMM would be immune to changes in temperature; however, it is practically impossible to construct such an instrument and even if it were possible, the component to be measured would still be affected by changes in temperature. The next best solution would be a CMM that would react to temperature in the same way as the component being measured. However, with the diversity of engineering materials now in use this is also impracticable. CMM manufacturers therefore minimise the structural distortion of the CMM caused by the difference in thermal expansion coefficients of each component, by employing a symmetrical design wherever possible. One manufacturer now uses hollow granite for the structural members; these have low weight while retaining granite's favourable thermal characteristics. In addition, covers and bellows are normally used to enclose the internal structural and moving members of the CMM therefore minimising the effect of ambient temperatures changes. The user should regularly check that these covers are in good condition. Points to note are listed below.

- Thermal insulation should be used to enclose the inspection area or in the case of in-line CMMs an enclosure (figure 44) should be used.
- The air temperature surrounding the CMM should be controlled by the installation of a heat exchanger or an air conditioning unit.
- Care should be taken to maintain the proper temperature within the surrounding area; a difference in temperature between the CMM and the workpiece can result in measurement errors.
- If the probing is commenced as soon as the workpiece is placed on the CMM table, temperature changes during measurement may produce significant errors, especially if the workpiece is still warm from machining operations. The workpiece should, therefore, be allowed to remain at ambient temperature until the user is satisfied that equalisation of temperature has taken place.


**Figure 44 An enclosed CMM, courtesy of Hexagon Metrology**

Compensation for thermal expansion and thermal distortion errors can be made by a combination of hardware and software solutions known as adaptive structural thermal compensation technology. The system includes a number of sensors capable of reading the temperature on the structure of the machine and software algorithms that extrapolate expansion and distortion values from the data. The software is able to compensate for the current thermal state of the machine so that the influence of temperature variations is minimised over a wide range. The resulting CMM is insensitive to shop floor temperature variations, as well as spatial and temporal thermal gradients. However, for best results care must still be taken to ensure that workpiece temperature effects are taken into account. Figure 45 shows how even with the use of temperature compensation there is still an uncertainty in length measurement due to the uncertainty in the thermal expansion coefficient and the temperature measurement. The example shown in figure 45 is for a 1 m steel bar ($\alpha = 11.5 \times 10^{-6}$ K$^{-1}$) with an uncertainty in $\alpha$ of $0.58 \times 10^{-6}$ K$^{-1}$ and an uncertainty in temperature of 0.1 K.

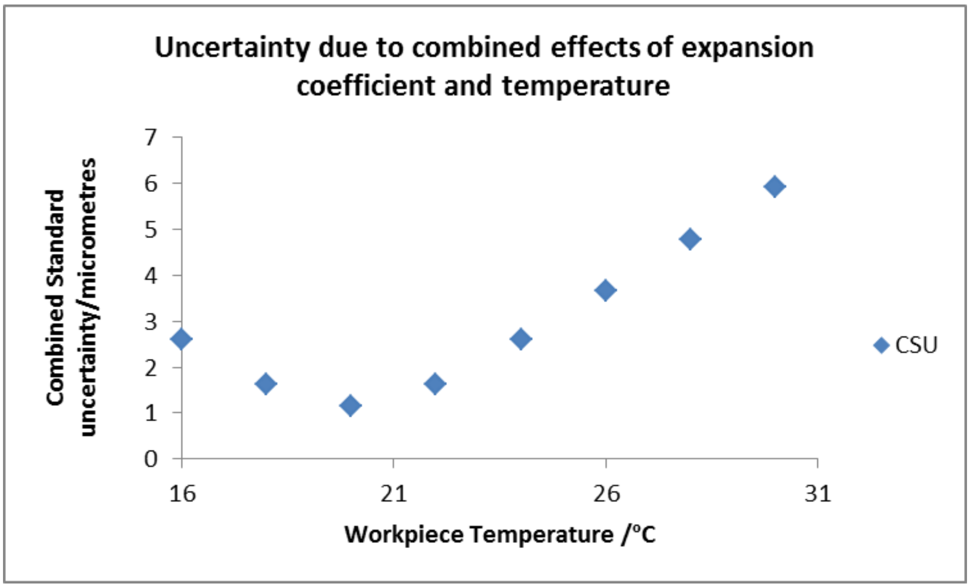



**Figure 45 Combined standard uncertainty (csu) due to combined effects of the uncertainty in the temperature measurement and uncertainty in thermal expansion coefficient for a 1 m steel bar (adapted from Coordinate measuring machines and systems).**

However, if we compare figure 45 with what happens if you do not make any temperature compensation we get figure 46.

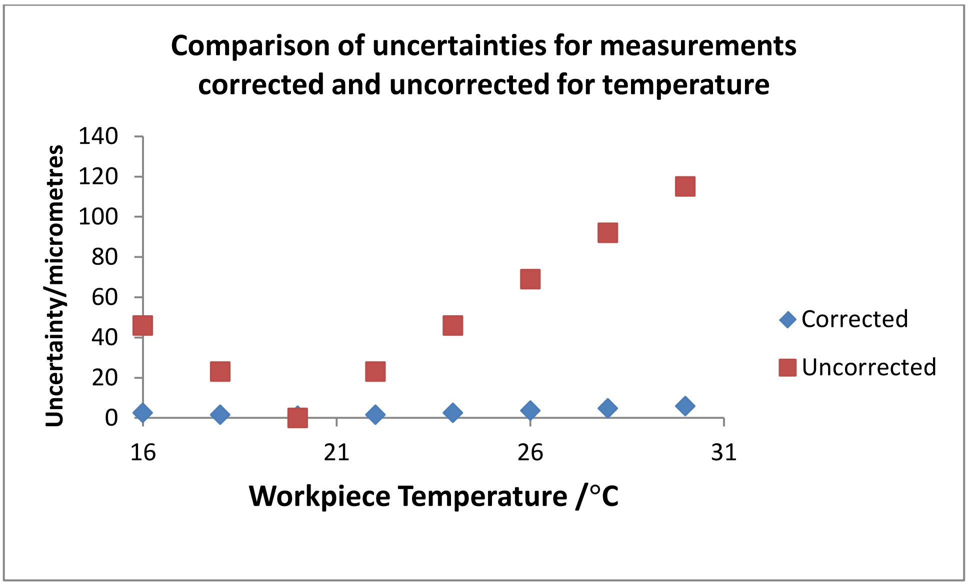



**Figure 46 Comparison of uncertainty for measurements corrected for temperature (blue) and the measurement error through not correcting (red)**

The aim when installing a CMM should always be to keep thermal gradients to a minimum. The second aim should be to minimise changes of temperature with time. The final aim should be to operate the CMM at a temperature close to 20.0 °C. If the machine is not in a controlled environment then

- avoid opening or closing external doors and windows during a measurement;
- do not turn on heating during the measurement;
- shield the machine from heat sources (for example, other machines); and

- shield the machine from direct sunlight.

## The effect of vibration

Vibration is a factor that can significantly affect the accuracy achieved by CMMs. Machines used for in-line measurement must have sufficient resistance to vibrations caused by machine tools and other equipment within the vicinity. Major design considerations include a high natural frequency of the CMM in order to minimise the effect of low frequency vibrations, rigid structural members and the use of air bearings that require no contact between the bearing and the bearing surface during use, resulting in zero wear and no noise or vibration.

In cases where the vibration levels are too high the user can improve the situation by installing an appropriate vibration isolation system tailored to his production environment.

The starting point is the information provided by the CMM manufacturer on the maximum levels of vibration the machine can withstand. The next step is to relate this information to the worst-case vibration characteristics on the production floor at the site where the CMM is to be installed. Vibration on most production floors is usually the result of either steady state or induced vibration or shock. A detailed knowledge of the nature and magnitude of the vibration levels at the CMM installation site is therefore essential if the CMM is to perform to specification. A vibration site survey can identify the amplitudes of these vibrations and the frequencies at which they occur. Comparison of this data with the manufacturer's allowable floor vibration limits then enables the correct selection of an isolation system to reduce the transmission of floor vibration to within the CMM’s operating range. It is important that the correct equipment and data analysis techniques are used in the site survey since errors here could seriously undermine the final choice of isolation system.

The most commonly used isolators for CMMs, include elastomeric (rubber) pads, coil springs and pneumatic isolators, and the information provided by the isolator manufacturer on their vibration reduction characteristics should be studied before implementing them on a CMM. It should be noted that foundations or inertia masses might also be required in conjunction with the isolation system in order to increase system stability or to provide additional stiffness and support for the machine bases.

## Dust and cleanliness

Airborne dust from the production site can accumulate on the CMM’s mating surfaces, causing a slow deterioration in accuracy or possibly a system malfunction. For dust protection, machines normally have built-in dust wipers on all axes; dust covers and bellows protect the sliding scales. Regular maintenance will ensure that ingress of dust and consequent wear of mating surfaces is kept to a minimum. Cleaning of the workpiece, stylus and calibration spheres should always be made with lint-free materials.

An effective measure to prevent dust from entering the working environment of the CMM is the use of a fan to maintain an air pressure that is slightly higher within the area or enclosure. The principle of this is that air will flow from the high-pressure area to the low-pressure area thereby preventing dust from entering the atmosphere surrounding the machine. Consideration should also be given to installing air filtration in the CMM enclosure, making use of air locks and TacMats, and the wearing of suitable overalls and over shoes by the operator since much of the dust can be fibres shed from unsuitable clothing.

## Chapter summary

- Beware of the effect of temperature
- Keep all items clean
- Take precautions to minimise dust
- Select a low vibration installation site and take appropriate vibration isolation measures

# Summary

12

**IN THIS CHAPTER**

- Summary

This measurement good practice guide has provided an overview of the various considerations when developing a strategy for measuring a component on a CMM. The contents of this guide can be summarised as follows

- choose appropriate datum;
- pay attention to the probe qualification;
- choose an appropriate number and distribution of points to represent a feature;
- beware of alignment and projection problems;
- beware of temperature and other environmental effects;
- keep everything clean;
- beware of the problem of partial arcs; and
- have in place adequate control of CNC programs.

# Glossary of terms

# 13

**IN THIS CHAPTER**

- A glossary of terms.

## Glossary of terms

Terms defined below are based on the VIM, 3rd edition, JCGM 200:2008 (*International Vocabulary of Metrology - Basic and General Concepts and Associated Terms*) and ISO 10360 Parts 1 and 2.

| | |
|---|---|
| Accuracy | For touch trigger probes the accuracy is stated in terms of the uncertainty of measurement arising from error sources such as repeatability and pretravel variation. |
| Analogue probe | A proportional probe in which the displacement of the stylus is represented by a probe continuously variable output voltage or current proportional to the displacement. |
| CMM | A measuring system with the means to move a probing system and capability to determine spatial coordinates on a workpiece surface. |
| Contacting probing system | A probing system which needs material contact with a surface being measured in order to function. |
| Probe | The device that generates the signal(s) during probing. |
| Probing system | A system consisting of a probe and, where present, probe extensions, probe changing system, stylus, stylus changing system and stylus extensions. |
| Probe head | A device fitted to the ram of the CMM that carries the probe mounting connector. Probe heads may have fixed orientation or may articulate to provide re-orientation of the probing axis. Articulating heads may be manually operated or motorised. |
| Proportional probe | A displacement measuring probe that provides an output, which may be analogue or digital, proportional to stylus displacement over a defined operating range. |
| Probing system qualification | The establishment of the parameters of a probing system necessary for subsequent measurements. |
| Ram | The component of a CMM that carries a probing system. Also called the quill. |
| Requalification | Repetition of the qualification procedure that may be necessary after changing or moving components in the |

| | |
|---|---|
| | measurement path, or following a change to ambient temperature |
| Scanning Probe | A proportional probe that is passed over the surface of the workpiece in a continuous movement, sending data to the processor at a high rate. |
| Shank | A plain or tapered shaft for mounting a probe or probe head to the quill of the CMM. |
| Stylus | A mechanical device consisting of a stylus tip and shaft. |
| Stylus tip | The physical element that establishes the contact with the workpiece. |
| Touch trigger probe | A discrete point-taking type of contact probe. |

# Health and safety

# 14

**IN THIS CHAPTER**

- Mechanical
- Hazards associated with laser illumination
- Chemical

When using a CMM any local safety rules should be adhered to and a risk assessment undertaken before starting the work. If working at a customer's site be aware of any evacuation procedures and any extra risks such as moving vehicles and overhead cranes. Some specific things to look for when carrying out a risk assessment are listed below.

## Mechanical hazards

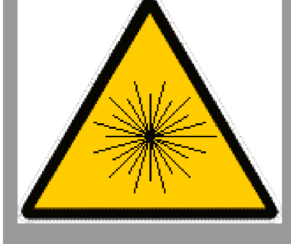
Many of the items measured on a CMM are relatively heavy. The appropriate lifting techniques and equipment should always be used and safety shoes worn. Operators should wear laboratory coats or overalls for safety reasons and to prevent fibres shed from clothing from falling on items being measured.

Machines under direct computer control may move without warning. The operator should stand back from the machine during an automatic run.

## Hazards associated with laser illumination

Some optical trigger probes employ class 2 laser radiation therefore the appropriate laser safety precautions should always be observed. It goes without saying that any users of such probes should be trained in their safe usage. Some general guidance is given in the box below.

**NOTE**



**Important safety information**
A rough guide to laser safety stickers would say that any laser system with a visible output of less than 0.2 mW is considered a Class 1 laser and is not dangerous. While any visible laser of between 0.2 mW and 1.0 mW output power is considered a Class 2 and relies on sensible people blinking before any damage is done to their vision. Class 3B refers to power levels above 5.0 mW and can cause damage to your retina and should on the whole be treated with a great deal of respect because once damaged your eyes are irreparable and irreplaceable! Class 4 involves powers above 0.5 W for which intrabeam viewing and skin exposure is hazardous and for which the viewing of diffuse reflections may be hazardous. These lasers also often represent a fire hazard. (For a more detailed description of the classes have a look at BS EN 60825-1 2014)

## Chemical hazards

Chemicals may need to be used for cleaning purposes. Make sure the manufacturer's safety guidance is followed and the relevant personal protective equipment worn. Substances may be covered by the COSHH regulations.

# Appendices

# 15

**IN THIS CHAPTER**

- Appendix A Links to other useful sources of information.
- Appendix B Further reading.
- Appendix C User Requirement
- Appendix D Functional Specification
- Appendix E Testing

# Appendix A Links to other useful sources of information

## A.1 National and International Organisations

### A.1.1 National Physical Laboratory

*"When you can measure what you are speaking about and express it in numbers you know something about it; but when you can not express it in numbers your knowledge is of a meagre and unsatisfactory kind."*

Lord Kelvin, British Scientist (1824 – 1907)

The National Physical Laboratory (NPL) is the UK's national measurement institute and is a world-leading centre of excellence in developing and applying the most accurate measurement standards, science and technology available. For more than a century NPL has developed and maintained the nation's primary measurement standards. These standards underpin an infrastructure of traceability throughout the UK and the world that ensures accuracy and consistency of measurement.

NPL ensures that cutting edge measurement science and technology have a positive impact in the real world. NPL delivers world-leading measurement solutions that are critical to commercial research and development, and support business success across the UK and the globe.

Good measurement improves productivity and quality; it underpins consumer confidence and trade and is vital to innovation. NPL undertake research and shares its expertise with government, business and society to help enhance economic performance and the quality of life.

NPL's measurements help to save lives, protect the environment, enable citizens to feel safe and secure, as well as supporting international trade and companies to innovation. Support in areas such as the development of advanced medical treatments and environmental monitoring helps secure a better quality of life for all.

NPL employs over 500 scientists, based in south west London, in a laboratory, which is amongst the world's most extensive and sophisticated measurement science buildings.

The National Physical Laboratory is operated on behalf of the National Measurement Office by NPL Management Limited, a wholly owned subsidiary of Serco Group plc. For further information: Switchboard 020 8977 3222 | www.npl.co.uk/contact

### A.1.2 National Institute of Standards and Technology (NIST)

NIST is the equivalent of NPL in the United States of America. Founded in 1901, NIST is a non-regulatory federal agency within the U.S. Department of Commerce. NIST's mission is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve quality of life.

The NIST web site at www.nist.gov often contains documents relevant to this guide in Adobe PDF.

### A.1.3 EURAMET

The European Association of National Metrology Institutes (EURAMET) is a Regional Metrology Organisation (RMO) of Europe. It coordinates the cooperation of National Metrology Institutes (NMI) of Europe in fields such as research in metrology, traceability of measurements to the SI units, international recognition of national measurement standards and related Calibration and Measurement Capabilities (CMC) of its members. Through knowledge transfer and cooperation among its members EURAMET facilitates the development of the national metrology infrastructures.

EURAMET serves the promotion of science and research and European co-operation in the field of metrology.

This is realized by the following measures in particular:

- development and support of European-wide research co-operation in the field of metrology and measurement standards;
- development, regular updating and implementation of a European Metrology Research Programme (EMRP);
- support of members and associates when applying for research funds for the purpose of European cooperative projects;
- co-ordination of joint use of special facilities;
- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards;
- technical co-operation with metrology institutes beyond EURAMET and with other regional and international metrology organisations;

- performing the tasks of a Regional Metrology Organisation (RMO) with the objective of worldwide mutual recognition of national measurement standards and of calibration and measurement certificates;
- promotion and co-ordination of scientific knowledge transfer and experience in the field of metrology;
- representing metrology at the European level and promoting best practice to policy and political decision makers with regard to the metrological infrastructure and European co-operation;
- co-operation with European and international organisations responsible for quality infrastructure, in particular by participation in the preparation of harmonized technical documents.

For more information visit the EURAMET web site at: www.euramet.org

### A.1.4 Institute for Geometrical Product Specification

More information about GPS can be found at the Institute for Geometrical Product Specification website www.ifgps.com. Click on resources for more information on GPS.

## A.2 Networks

### A.2.1 Mathematics and Modelling for Metrology (MMM)

MMM is an programme that underpins the NMS, focussing on the use of mathematics and computing in metrology. It aims to achieve a balance between research and development, whilst also extending the range of techniques and applications available to meet the continually changing needs of metrology. The overall aim of the Programme is to tackle a wide range of generic issues, some of which are problems in metrology that require the application of established software engineering practices, whilst others require advances in mathematics, software engineering or theoretical physics. The programme, thus, includes work in metrology, mathematics, software and theoretical physics, with strong links between the various disciplines.

Further details can be found at website: http://www.npl.co.uk/category/384

## A.3 National and International Standards

### A.3.1 British Standards Institution (BSI)

BSI started in 1901 as a committee of engineers determined to standardise the number and type of steel sections in order to make British manufacturers more efficient and competitive. The BSI Group is now the oldest and arguably the most prestigious national standards body in the world and is among the world’s leading commodity and product testing organisations. Website www.bsi-group.com.

### A.3.2 International Organisation for Standardization (ISO)

The International Organization for Standardization (ISO) is a worldwide federation of national standards bodies from some 140 countries.

The mission of ISO is to promote the development of standardisation and related activities in the world with a view to facilitating the international exchange of goods and services, and to developing cooperation in the spheres of intellectual, scientific, technological and economic activity.

ISO's work results in international agreements that are published as International Standards.

Further information on ISO can be found at: www.iso.ch

**The following BS and ISO specifications are relevant to this guide.**

ISO 10360-1: 2000 Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM)—Part 1: Vocabulary

ISO 10360-2: 2009 Geometrical product specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 2: CMMs used for measuring linear dimensions

BS 7172:1989 British Standard Guide to Assessment of position, size and departure from nominal form of geometric features.

ISO 1101:1983 *Technical drawings -- Geometrical tolerancing -- Tolerancing of form, orientation, location and run-out -- Generalities, definitions, symbols, indications on drawings*

ISO 1101:1983/Ext 1:1983 *Toleranced characteristics and symbols — Examples of indication and interpretation* (available in English only)

ISO 5459:1981, *Technical drawings-Geometric Tolerancing - Datums and datum systems for geometrical tolerances*

ISO 15530-3. *Geometrical product specifications (GPS) – Coordinate Measuring Machines (CMM): Techniques for evaluation of the uncertainty of measurement Part 3: Use of calibrated workpieces ISO International Technical specification, International Standards Organisation.*

Document *ASME Standard Y14.5M-1994 Dimensioning and Tolerancing* may also be of interest to users of this guide.

## A.4 Traceability

Traceability in measurement is the concept of establishing a valid calibration of a measuring instrument or measurement standard, by a step-by-step comparison with better standards up to an accepted or specified standard. In general, the concept of traceability implies eventual reference to an appropriate national or international standard.

The National Physical Laboratory is the United Kingdom's national standards laboratory. It operates at the heart of the National Measurement System (NMS) which is the infrastructure designed to ensure accuracy and consistency in every physical measurement made in the UK. Chains of traceability link UK companies’ measurements directly to national standards held at NPL.

For the majority of industrial applications, companies can establish a link to national measurement standards through the calibration and testing services offered by United Kingdom Accreditation Service (UKAS) accredited laboratories, which are in turn traceable to NPL. However, for challenging or novel measurements to the highest standards of accuracy, which are not catered for by UKAS-accredited laboratories, NPL can often provide a traceable measurement solution directly to industry.

The United Kingdom Accreditation Service is the sole national accreditation body recognised by government to assess, against internationally agreed standards, organisations that provide certification, testing, inspection and calibration services.

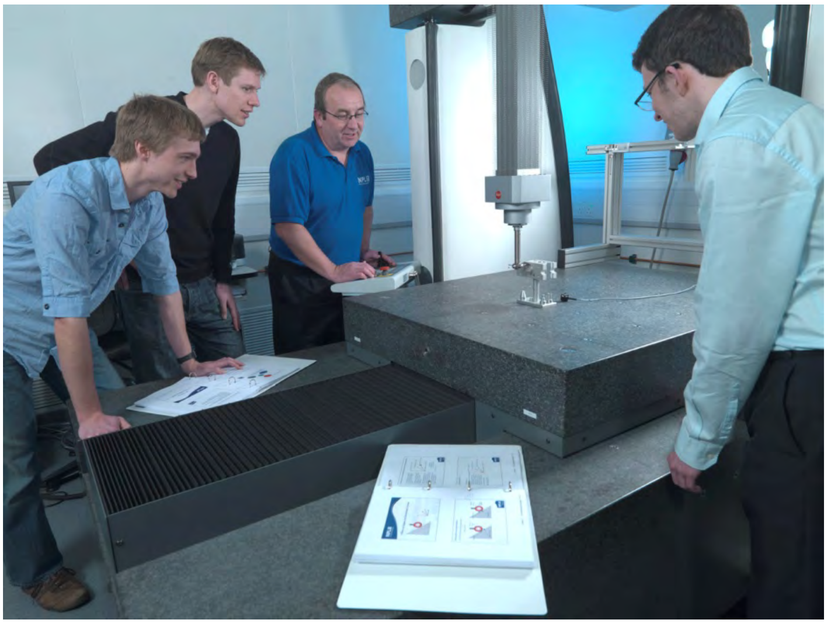
Accreditation by UKAS demonstrates the competence, impartiality and performance capability of these evaluators.

UKAS is a non-profit-distributing private company, limited by guarantee. UKAS is independent of Government but is appointed as the national accreditation body by the Accreditation Regulations 2009 (SI No 3155/2009) and operates under a Memorandum of Understanding with the Government through the Secretary of State for Business, Innovation and Skills.

UKAS accreditation demonstrates the integrity and competence of organisations providing calibration, testing, inspection and certification services.

Further information on UKAS can be found at: www.ukas.com.

## A.5 Training courses



### A.5.1 Dimensional Measurement Training: Level 1 – Measurement User

A three day training course introducing measurement knowledge focusing upon dimensional techniques.

***Aims & Objectives***

To provide:

- the underpinning knowledge and expertise for anyone who uses measurement tools or requires an appreciation of the importance of measurement,
- the principle knowledge and practical training for people who are required to use dimensional measurement techniques to complete their daily tasks; and
- the tools to instil and encourage questioning culture.

Enabling:

- An understanding of the fundamentals of standards, traceability, calibration, uncertainty, repeatability, drawing symbols and geometrical tolerances, the importance of the relationship between tolerances and measuring equipment and be able to question the measurement.

Level 1 is applicable to all industrial sectors as a stand-alone qualification or as a building block for further NPL Dimensional Measurement Training levels – 2 & 3.

***Course Content***

**Day 1 - Geometric Product Specification (GPS) A**
Including what is GPS, drawing practice and geometrical tolerances.

**Day 2 - Measurement Principles and Methods A**
Including successful measurements, standards, traceability, calibration, uncertainty, units, relationship between tolerances and measuring equipment using micrometers and callipers, repeatability and reproducibility of measurements.

**Day 3 - Measurement Principles and Methods B**
Including the relationship between tolerances and measuring equipment by the use of height gauges, dial test indicators, dial gauges, plug gauges, gap gauges and temperature effects.

NB: Fundamental Measurement Calculation is incorporated into all 3 days including powers, scientific notification and triangles. This is achieved by understanding the relationship of these calculations when applied to tolerance zones and practical measuring tasks.

A workbook of evidence must be completed successfully during the training course and, where required, post assessment tasks can be set for each individual to be completed in the workplace.

### A.5.2 Dimensional Measurement Training: Level 2 - Measurement Applier

A four day training course for those who have a good basic understanding of measurement principles gained through the Level 1 training course.

***Aims & Objectives***

To provide:

- the underpinning knowledge and expertise for anyone who uses measurement tools or requires an appreciation of the importance of measurement,
- the principle knowledge and practical training for people who are required to use co-ordinate measurement techniques to complete their daily tasks; and
- the tools to instil and encourage questioning and planning culture

Enabling:

- a visible return on investment for a manufacturing organisation in the form of various production cost savings and an upskilled workforce,
- a reduction in re-work time and waste on the production line - faults and problems will be detected earlier in the production process; and
- An in-depth appreciation of *why* measurement is carried out and not simply *how*

Level 2 is applicable to all industrial sectors as a stand-alone qualification or as a building block for further NPL Dimensional Measurement Training levels – 3 & 4.

A workbook of evidence must be completed successfully during the training course and, where required, post assessment tasks can be set for each individual to be completed in the workplace.

***Course Content***

**Geometric Product Specification (GPS) B**
Content covered:
GPS standards; Envelope tolerance; Size Principles; ISO Limits and Fits Projected tolerance; Free state condition; Virtual condition; Maximum Material Condition principles; Geometrical tolerancing measurements using first principle measuring equipment; Surface texture principles.

**Measurement Principles and Methods C**
Content covered:
Calibration; Uncertainties; Traceability; Procedures; First Principle Measurement; Angle plate; Gauge blocks; Surface plate; Height micrometer; Sine bar or sine table.

**Process Control A**
Content covered:
Statistical Process Control theory; Variation – common, special causes; Prevention versus detection; Collecting and calculating data when using measuring tools; Callipers; micrometers; Basic charts – Tally chart/Frequency Table, Histogram, Control Chart; Reacting to variation; Benefits of process control; Standard deviation; Capability indices; Fundamentals of Gauge R&R.

**Measurement Principles and Methods D**
Content covered:
Taper calculations; Angles; Diameters; Searching for triangles; Chords; Radians; Manipulation of formula.

**Co-ordinate Principles A**
Content covered:
***Application of equipment:*** First principles; Co-ordinate Measuring Machine; Optical and vision machines; Articulating arm; Laser tracker; Projector; Microscopes; Height gauge with processor; Contour measurement equipment.
***Machine performance***: Calibration standards; Self-verification/artefacts; Measurement volume.
***Alignment Techniques***: 321/point system alignment; Flat face alignment; Axes alignment; Car line/engine centre line.
***Machine appreciation:*** Ownership; Care; Respect; Cost; Contribution to the business.
***Work Holding:*** Fixturing; Rotary table; Clamping; How to hold the part; Influence of component weight, size, shape; Free state; Restrained state.
***Co-ordinate geometry***: Points; Plane; Line; Circle; Cylinder; Cone; Sphere; Ellipse.
***Sensor Types***: Probing Strategies; Relevant standards; Environment.
***Measurement Strategies:*** Number of points; Partial arc; Contact/non contact.

**Co-ordinate methods A (OEM Training - equipment specific)**
Content covered:
First principles; Co-ordinate Measuring Machine; Optical and vision

machines; Articulating arm; Laser tracker; Projector; Microscopes; Height gauge with processor; Contour measurement equipment.

### A.5.3 Mitutoyo training courses

The Mitutoyo Institute of Metrology offers qualifications and training in over thirty metrology related subjects. Mitutoyo training programmes are vocation based and are accredited with the Open College Network (http://www.nocn.ac.uk) for a qualification in Dimensional Metrology. These credits in turn, contribute towards the evidence route of the Technical Services Engineering NVQ recently accredited by EMTA (Engineering and Maritime Training Authority). These courses are recognised nationally and are available in various areas of metrology.

See the Mitutoyo training pages http://www.mitutoyo.co.uk/service-and-support/training/ for more information.

### A.5.4 NPL E-Learning

Access over a century of **measurement knowledge** and **state-of-the-art techniques**, quality assured from the UK's National Measurement Institute. NPL's new e-Learning programme delivers measurement training, globally accessible across PCs and mobile devices, helping to provide confidence, value and performance from your measurement systems.

Engage with cost-effective on-demand content, globally accessible through an easy-to-use professional solution, compatible across devices.

NPL e-Learning offers:

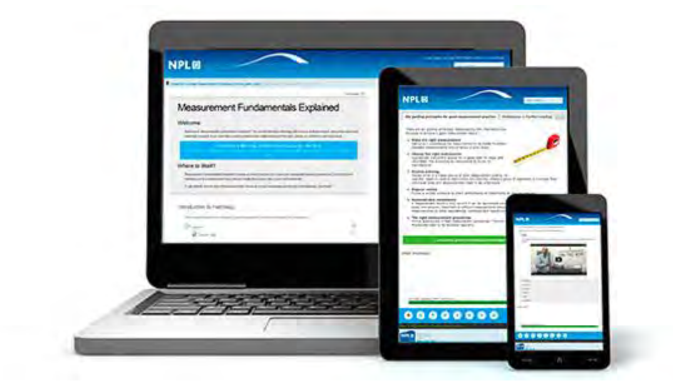
- metrology training courses;
- free online open units; and
- free *Glossary of Metrology Terms*.

Ready for:

- apprenticeship programmes;
- national curricula; and
- workplace learning schemes.

Measurement just got simpler, and is now available to you **whenever you want and wherever you like – sign up now for free**.

http://www.npl.co.uk/e-learning




- Save time - Reduce time away from the job and fit training into busy work schedules
- Save money - Save travel costs and adjust training to your own schedule
- Take the classroom with you - Have your lessons anytime, anywhere
- Control your learning - Sequence your own learning and access only the materials you require
- Own your progression - Assess your progress and receive immediate feedback

# Appendix B Further reading

Measurement of Artefacts using repositioning methods, NPL Report CLM2 M G Cox, N R Cross, A B Forbes and G N Peggs

'Traceability of CMM Measurements: Influence of the workpiece error on the measurement uncertainty (virtual workpiece)' by Maurice Cox

Meas. Sci. Technol. 8 (1997) 837-848 Some performance characteristics of a multi-axis touch trigger probe F M M Chan, E J Davis, T G King and K J Stout.

Precision Engineering 19:85-97, (1996) Error compensation for CMM touch trigger probes
W. Tyler Estler, S. D. Phillips et al.

Fundamentals of Touch Trigger Probing by David Coleman and Fred Waters
ISBN 0 9512010 1 8 Touch Trigger Press (1997)

Fundamentals of Dimensional Metrology, Sixth Edition Connie L. Dotson.

Co-ordinate metrology Technology and Application by Han Joachim Neuman (Verlagmoderne Industrie) Translation of 'Koordinaten Messtechnik' by Ursula Brock.

Other information is published regularly in Quality Manufacturing Today, Measurement Science and Technology, Metrologia, Measurement and Precision Engineering.

A conceptual Data Model of Datum Systems Journal of Research of the National Institute of Standards and Technology Volume 104, Number 4, July-August 1999.

Coordinate Measuring Machines and Systems, Second Edition, Robert J. Hocken

CMM Verification, Measurement Good Practice Guide No. 42, July 2011

CMM Probing, Measurement Good Practice Guide No. 43, July 2001

# Appendix C User Requirement

**USER REQUIREMENT**

Date:

| |
|---|
| Customer's Name: |
| Workpiece Description: |
| Drawing No: |
| Order/Internal OrderNo:<br><br>Date: |
| Uncertainty Required:<br>(*E.g. 0.1 μm*) |

| |
|---|
| Description of User Requirement (*if customer order has insufficient information*), otherwise attach copy of Purchase Order. |
| Relevant British/International Standards:<br>(*E.g. ISO 10360-2, 1994, etc.*) |

# Appendix D Functional Specification

## 1. CMM to be used

| | |
|---|---|
| **CMM** | |
| **Location** | |
| **Serial Number** | |
| **Machine MPEe** | |
| **Machine software and version number** | |

## 2. Stylus Configuration

**Stylus System:**

| | | | | | |
|---|---|---|---|---|---|
| **Stylus Number/Name** | | | | | |
| **Length of Stylus (mm)** | | | | | |
| **Diameter of Ball (mm)** | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| **Stylus Number** | | | | | |
| **Length of Stylus (mm)** | | | | | |
| **Diameter of Ball (mm)** | | | | | |

| | |
|---|---|
| **Probing Force:** | **Probing Speed/Dynamic:** |
| **Stylus System:** | **Stylus Name:** |

## 3. Stylus Qualification

| | |
|---|---|
| | **Manual** |
| | **Tensor** |
| | **Six points** |
| | **Other (*e.g.*, Leitz)** |

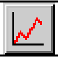
| | |
|---|---|
| **Confirm qualified at measuring speed/force (Y/N)** | |
| **Confirm qualification data stored (Y/N)** | |
| **Location of qualification data Path/File name:** | |

**Sketch or photograph of stylus system.**

## 4. Fixturing/Mounting arrangement

## 5. Co-ordinate System

## 6. Description of Probing Strategy

| ***Feature*** | ***No. of Points*** | ***Geometric Element*** |  |
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## 7. Temperature Correction

| | |
|---|---|
| **Specified Ambient Temperature (°C)** | |
| **Coefficient of Expansion** | |

## 8. Description

| | |
|---|---|
| **No. of Measuring Runs** | |
| **Description of Programme:** | |

## 9. Data Analysis

## 10. Presentation of Results

*Description of results to be output for generation of calibration certificate*

## 11. Data storage

| Data stored on network drive? (Y/N) | Format data stored? |
|---|---|
| Path/File name: | |

| | Name | Signature | Date |
|---|---|---|---|
| Operator | | | |
| Reviewed by | | | |

# Appendix E Testing

**TESTING (CNC PROGRAMME)**

| | |
|---|---|
| **CNC Programme Name:** | **Version No:** |
| **Written By:`** | **Date Written:** |
| **Checked By:** | **Date Checked:** |

| **Check List** | | **Comment** |
|---|---|---|
| 1. Is the code consistent with<br>(a) User Requirement?<br><br>(b) Functional Specification? | YES/NO<br><br>YES/NO | |
| 2. Are there any obvious errors in the programme? | YES/NO | |
| 3. Hand check calculations (where possible). Any inconsistencies? | YES/NO/ NA | |
| 4. Perform measurements of critical features by another method (if possible). Any inconsistencies? | YES/NO/ NA | |
| 5. Check all results against measurements made with a ruler. Any errors? | YES/NO | |
| 6. Run programme on an artefact of known size (if possible). Any inconsistencies? | YES/NO/ NA | |

| | **Name** | **Signature** | **Date** |
|---|---|---|---|
| **Operator** | | | |
| **Reviewed by** | | | |