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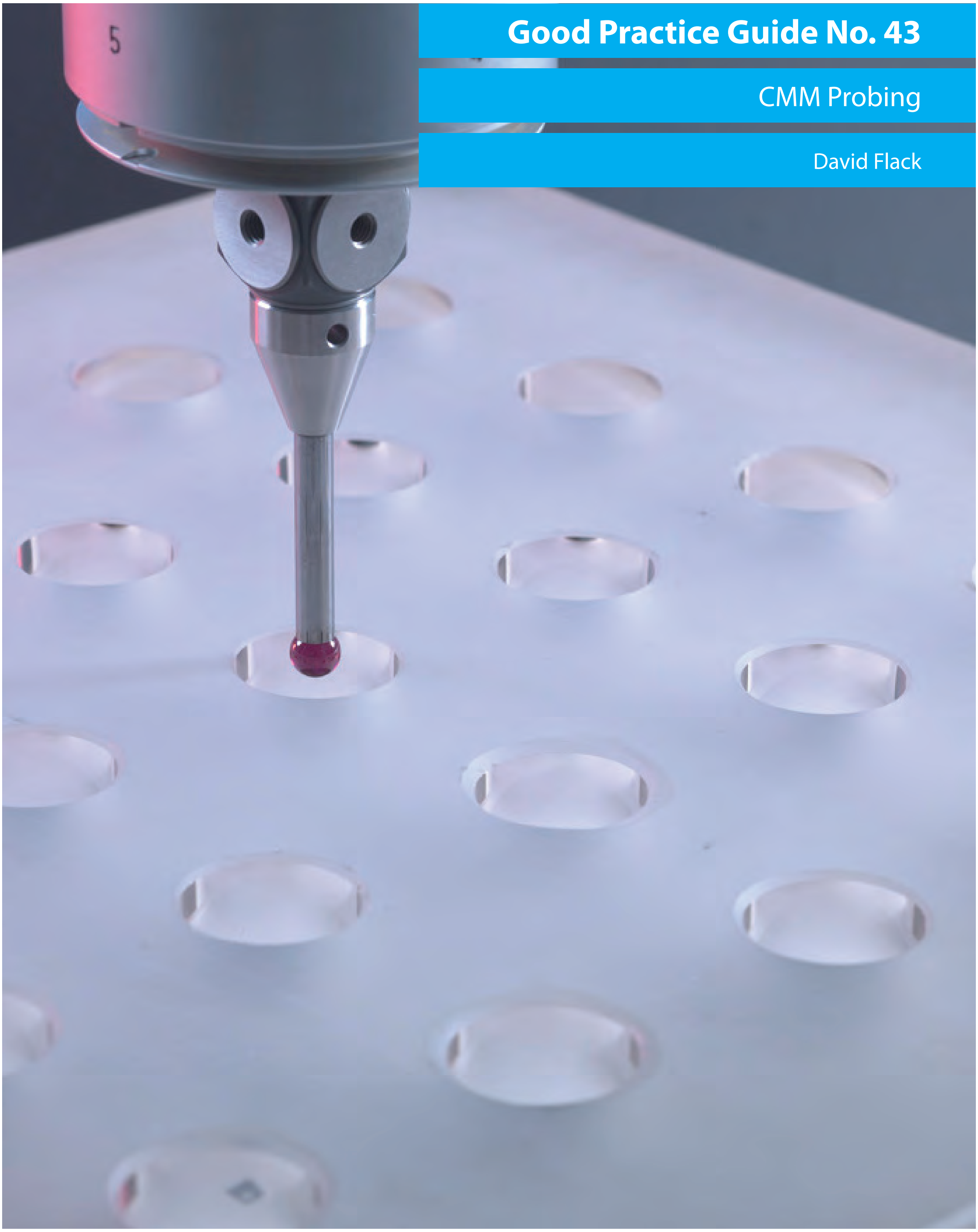

Good Practice Guide No. 43

CMM Probing

David Flack

National
Measurement
System

Issue 2

Measurement Good Practice Guide No. 43

CMM probing

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ABSTRACT

This guide is a general guide on probes and probing. It covers probing practice; types of contact probing systems, their advantages and disadvantages and how they work. It also covers the advantages and disadvantages of various stylus configurations; choosing the appropriate probing sphere size; and the use of non-contact sensors on CMMs. It is an update of a guide first published in 2001.

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Preface

The author hopes that after reading this Good Practice Guide you will be able to better understand CMM probing. 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

There are six guiding principles to good measurement practice that have been defined by NPL. They are:

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

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

The Right People: *Measurement staff should be competent, properly qualified and well informed.*

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

Demonstratable Consistency: *Measurements made in one location should be consistent with those made elsewhere.*

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

Introduction

1

IN THIS CHAPTER

- What this guide is about and what it is not
- Introduction to CMM probing

This measurement good practice guide provides an overview of probing technologies available for co-ordinate measurements and good practice in their use. It is an update to a guide first published in 2001 and has been updated to reflect changes in technology since the last issue.

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 use CMM probing technologies and apply appropriate good practice. This good practice guide is not intended to be an authoritative guide to the appropriate standards and the primary reference should always be the standards themselves.

Introduction to CMM probing

Co-ordinate measuring machines

A co-ordinate measuring machine is a measuring system with the means to move a probing system and capability to determine spatial coordinates on a workpiece surface. The Co-ordinate Measuring Machine has its origins in manually operated simple layout inspection equipment. With the development of numerical controlled (NC) machines in the 1950s for the production of complex components required in the United States aerospace programme and the subsequent introduction of computer numerical control (CNC) machines in the 1970s, production techniques were often more accurate than inspection equipment in general use.

A major factor in the evolution of the CMM was the invention in 1972 of the touch trigger probe (figure 1) by David McMurtry of Rolls-Royce[1]. The touch-trigger probe is a 3-D sensor capable of rapid, accurate inspection with low trigger force. When incorporated with precision linear measuring systems developed for CNC machines plus cheap and powerful computer hardware and software, this paved the way for highly accurate, automated inspection centres.

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[1] see Renishaw web site for further information

Figure 1 An early CMM probe (© Renishaw plc 1975)

CMMs are widely used in manufacturing industries for accurate, fast and reliable dimensional measurement of components. They are generally expensive to buy and maintain but their results are crucial to the manufacturing process.

Two forms of CMMs are available; manual and Direct Computer Control (DCC). Generally, use is made of manual CMMs for first-article inspection work. If the primary manufacturing environment is production orientated, a DCC machine is the usual choice.

DCC machines generally are the tools of choice for manufacturers who need to gather and analyse large amounts of data for maintaining control of the manufacturing process. The CMM is normally completely under DCC operation thereby eliminating any user influence on the quality of the recorded data.

CMM probes

CMMs can sense the surface using a variety of devices. These include touch trigger probes, analogue (measuring) probes, continuous scanning, and non-contact systems. The bulk of this guide will concentrate on touch trigger probes although found throughout this guide will be information on the other probing systems.

Mention will be made of some of the developments in probing technology since this the last issue of this guide including five-axis measurement probes, micro probes and fibre probes.

The guide discusses changes to the international standards relating to CMM probing since the last issue of this guide.

Design and principles of mechanical type touch trigger probes

2

IN THIS CHAPTER

- Design and principles of mechanical type touch trigger probes

The purpose of chapter 2 is to give the reader an introduction to the design principles of mechanical type touch trigger probes. Mechanical touch trigger probes are used with the majority of CMMs so it is important that the reader has an understanding of the principles behind their operation.

Design and principles of mechanical type touch trigger probes

The majority of CMMs use a touch trigger probe of some description. It is therefore helpful to have some basic understanding of how a touch trigger probe works.

The problem faced by the designer of touch trigger probes is that they must operate to a higher degree of accuracy than the accuracy required for the manufacture of the measured workpiece. Only by the application of kinematic principles can the design of the probe be such that its accuracy in operation does not depend entirely on its accuracy of manufacture.

The touch trigger probe therefore employs a form of kinematic location to retain a stylus in a highly repeatable manner. A typical mechanism (figure 3) consists of three cylindrical rods, each pressed against pairs of balls. This action constrains all six degrees of freedom of the stylus so that it always returns to the same position after deflection has taken place.

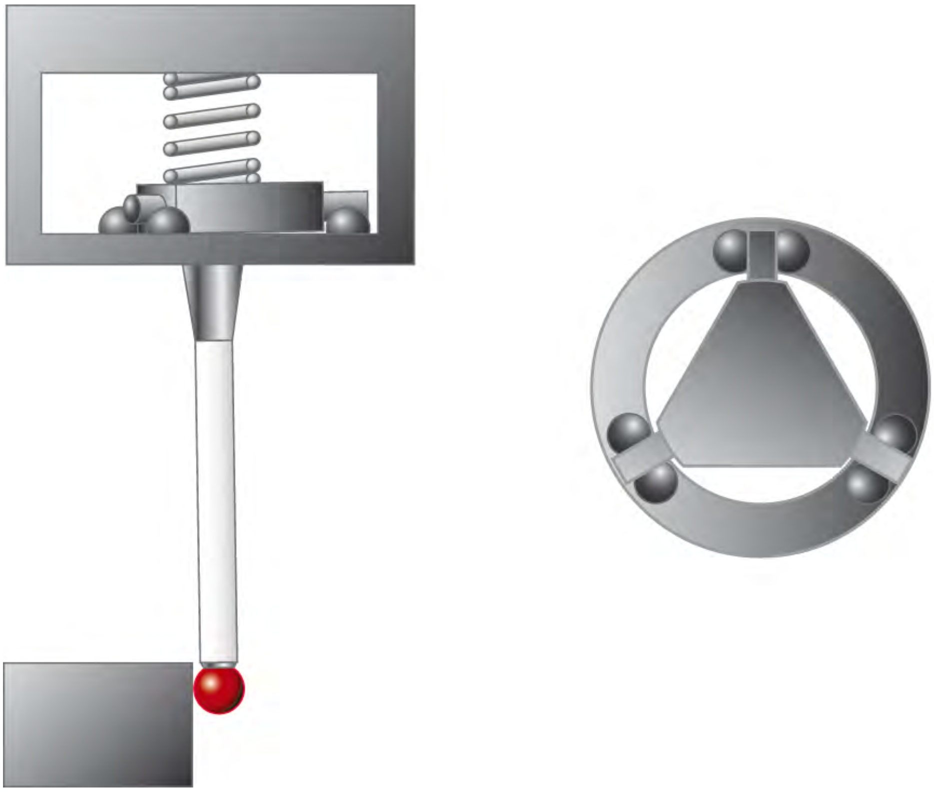
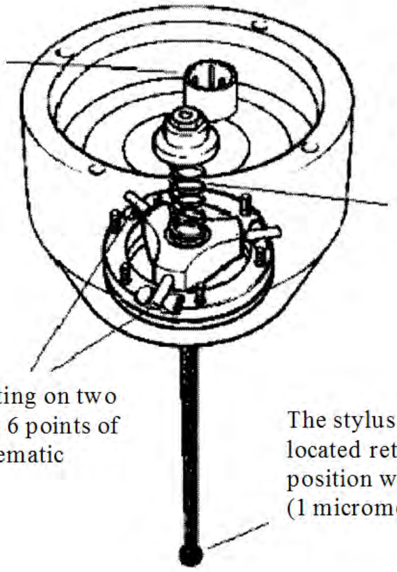


Figure 2 Schematic of a kinematic probe shown in seated position showing the three rods and three pairs of balls.(© Renishaw plc 2002)

An electrical circuit is made through contacts such that a trigger signal is generated whenever the stylus is deflected in any direction. At the moment of contact, this trigger signal notifies the computer to record the machine position (figure 4). These co-ordinates are then stored for subsequent use. The probe design allows further stylus deflection following contact, allowing time for the CMM to decelerate. As the stylus moves off the surface, the spring force (F_S in figure 5) causes the stylus mounting to reseat. The mechanism allows the probe to detect surfaces with sub-micrometre repeatability.



A trigger signal is generated on contact with the component surface and is used to stop the machine

A spring holds the stylus against the kinematic contacts and returns the probe to a seated position following contact between the stylus and the part

3 rods, each resting on two balls, providing 6 points of contact in a kinematic location

The stylus ball is uniquely located returning to the same position within 0.00004” (1 micrometre)

Figure 3 Cut-away drawing of a touch trigger probe (© Renishaw 1987)

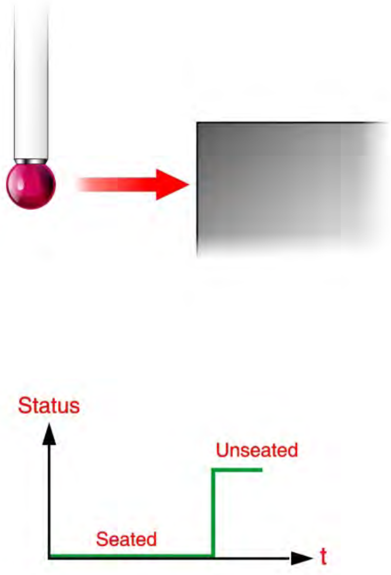


Figure 4 The moment of trigger. A trigger probe is in one of two states seated or unseated. Seated when not in contact with the workpiece and unseated when in contact. (©Renishaw plc 2006)

The main problem associated with the kinematic design of touch-trigger probes is that the geometry of the contacts results in slightly different contact forces being required to trigger the probe depending on the direction in which the stylus and surface meet. This variation leads to differing degrees of bending of the stylus between the moment when it makes contact with the workpiece to the instant when a trigger signal is generated. This deflection due to contact forces prior to the trigger signal is known as pre-travel. Pre-travel variation is the direction dependent range of this deflection. Stylus pre-travel can be accommodated by probe qualification against a calibrated reference sphere. Since pre-travel can vary according to the direction of probing, it is necessary to qualify the probe in the same direction as that of the intended measurement.

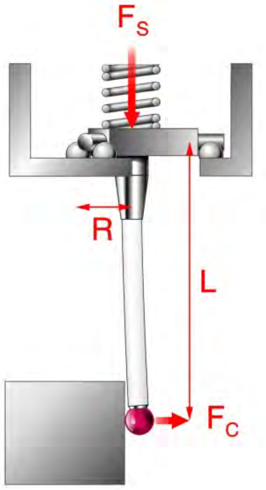


Figure 5 Forces that are in action during the trigger process. The amount of stylus bending at the point that a trigger occurs is known as the pre-travel. (© Renishaw plc 2014)

$$F_C \times L = F_S \times R$$

Figure 5 shows the forces that are in action during the trigger process. The contact force F_C generates a moment about the kinematics, resisted by the spring force F_S. The point of equilibrium is reached when the moment generated by F_C x L matches that generated by F_S x R.

The load F_C causes the stylus to bend. The amount of bending prior to the point that a trigger occurs depends of the magnitude of F_C needed to overcome the spring force, plus the length and stiffness of the stylus.

The amount of stylus bending at the point that a trigger occurs is known as the pre-travel. The pre-travel is direction-dependent, since it depends on the lever arm over which the spring force acts (R). As will be seen in the following figures, R changes depending on which direction the contact force acts relative to the probe mechanism, meaning the the magnitude of the contact force needed to trigger the probe also varies with probing direction.

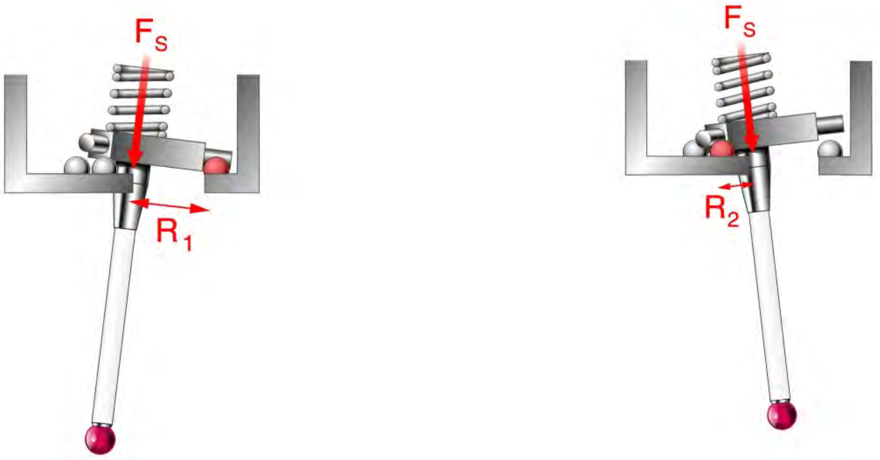


Figure 6 High force and low force direction. High force is a pivot about a single contact. For the low force direction the mechanism pivots about two contacts. (© Renishaw plc 2006)

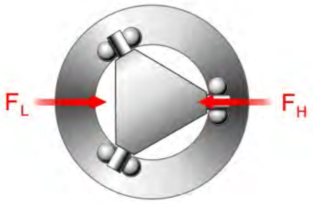


Figure 7 Image showing the low force (F_L) and high force (F_H) directions and its relationship to the number of pivots. (© Renishaw plc 2014)

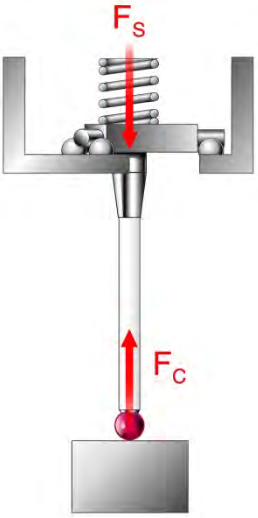


Figure 8 Axial probing (no mechanical advantage over the spring so the forces are equal. (© Renishaw plc 2006.)

Advances in probe design have helped to reduce this effect (figure 9 and figure 10). The use of three highly sensitive strain gauges situated in the probing head can detect contact forces building up between the stylus and workpiece (figure 11). In such designs, a trigger signal is generated at a very low force which is consistent in all directions therefore reducing the error due to direction- dependent forces.

Figure 9 A strain gauge probe mechanism. Note the one of the four silicon strain gauges is shown above the spring in red. Strain gauges trigger at forces that do not unseat the kinematics thus largely eliminating pretravel variation. (© Renishaw plc 2006)

Figure 10 A micro-strain gauge transducer (© Renishaw plc 2002)

The following list highlights the advantages of strain gauge probe technology over conventional kinematic probes.

- Increased stylus lengths can be supported (since contact forces are low, stylus bending is minimised). Use can be made of long styli without reducing the accuracy of measurement.
- They eliminate the lobing characteristic.
- Improved repeatability due to the low consistent trigger force.
- Contoured surfaces can be measured using 3-D operation whilst maintaining high accuracy.
- Increases probe life by up to a factor of ten compared to conventional kinematic probes.

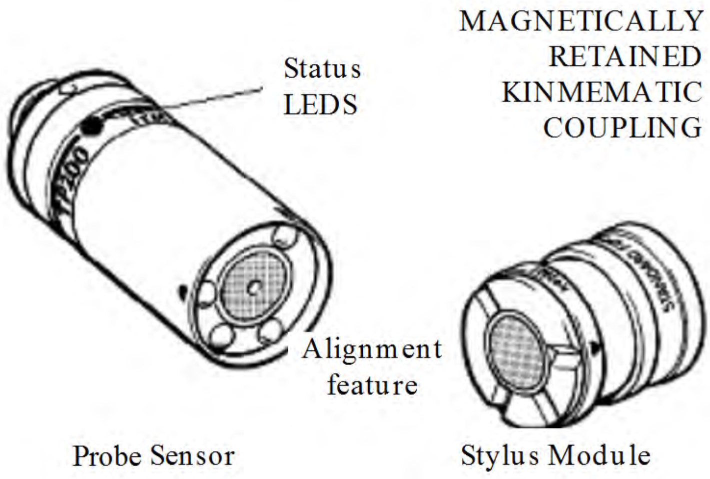


Figure 11 A micro strain gauge transducer (© Renishaw plc 2002)

Figure 11 shows how the stylus module is mounted on the probe *via* a kinematic joint. This joint allows rapid stylus changing capability and probe overtravel protection.

Further developments in trigger probe technology have seen the introduction of combined multi-sensing shock, strain and kinematic sensors. These types of probe can detect the minute shock of impact between the stylus and surface (figure 12), the force exerted on the stylus during displacement and the absolute displacement of the stylus.

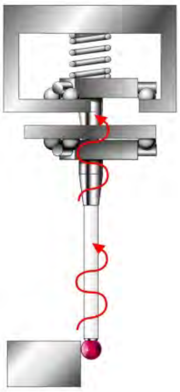


Figure 12 Piezo shock sensing. The shock wave travels up the stylus and is transmitted through kinematics. A piezo ceramic sensor detects shock of impact. Shock sensing is not 100 % reliable so is often backed by kinematic and strain sensors to conform shock © Renishaw plc 2006)

Chapter Summary

- understand the basic designs of touch trigger probes
- understand pre-travel variation

Analogue (measuring) probes

3

IN THIS CHAPTER

- Analogue (measuring) probes

The purpose of chapter 3 is to give the reader an introduction to the design principles of analogue measuring probes. Many high-accuracy CMMs incorporate analogue probes so it is important that the reader understands the principles behind their operation.

Analogue (measuring) probes

Many high accuracy co-ordinate measuring machines make use of analogue probes (figure 13 and figure 15). The probing system (figure 14) consists of three spring parallelograms that have a deflection range of typically ± 3 mm in the direction of the measuring axes. The movements in each direction are picked up by an inductive measuring system. Each parallelogram is clamped in its neutral position; the zero points of the inductive measuring systems are adjusted to this position. A moving coil system generates the measuring force when contact is made with the workpiece. As soon as the probing system has adjusted into near-zero position, the machine co-ordinates and the digitised residual deflections of the probe head (scanning unit) are transferred to the computer. For this probe, in high-speed travel, the probe head is pre-deflected in the probing direction. This ensures that the probe head can be stopped within its deflecting range in case of a contact or collision.

The main difference from a trigger probe is that measurement with an analogue probe is static which results in a considerable increase in accuracy. Analogue probes operate either in a free-floating mode (working in all three axes simultaneously) or in a clamped mode whereby the non-measuring axes are clamped.

The probes may employ passive sensors (device simply detects deflection) or use motors to control the deflection (active).

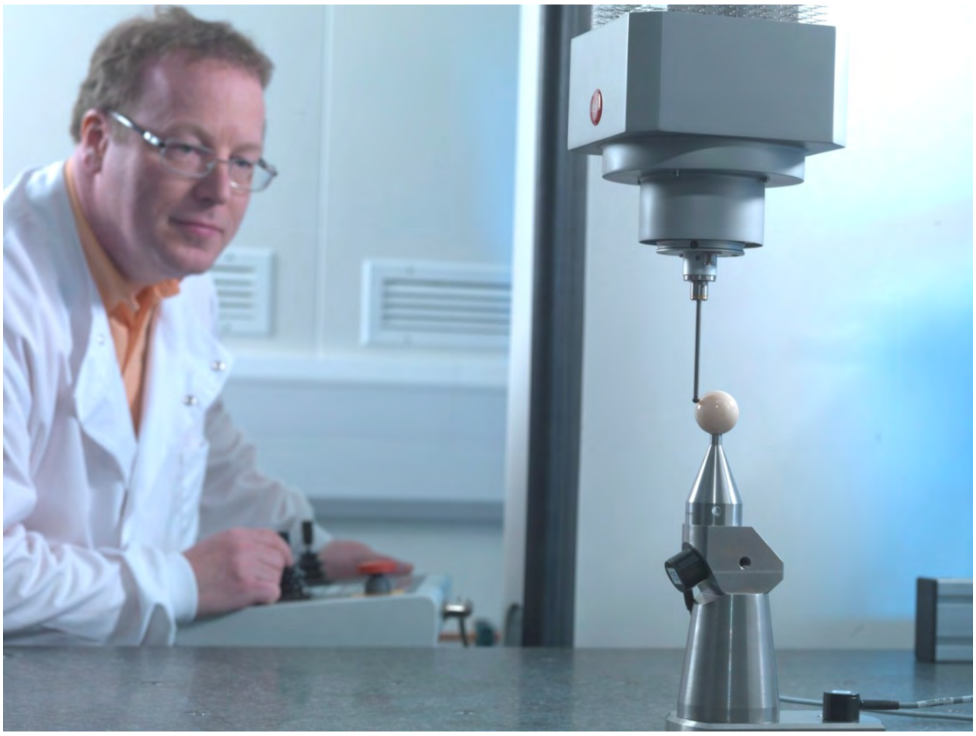


Figure 13 A CMM with an analogue probing system

Figure 14 An exploded diagram of an analogue probe head (©Zeiss)

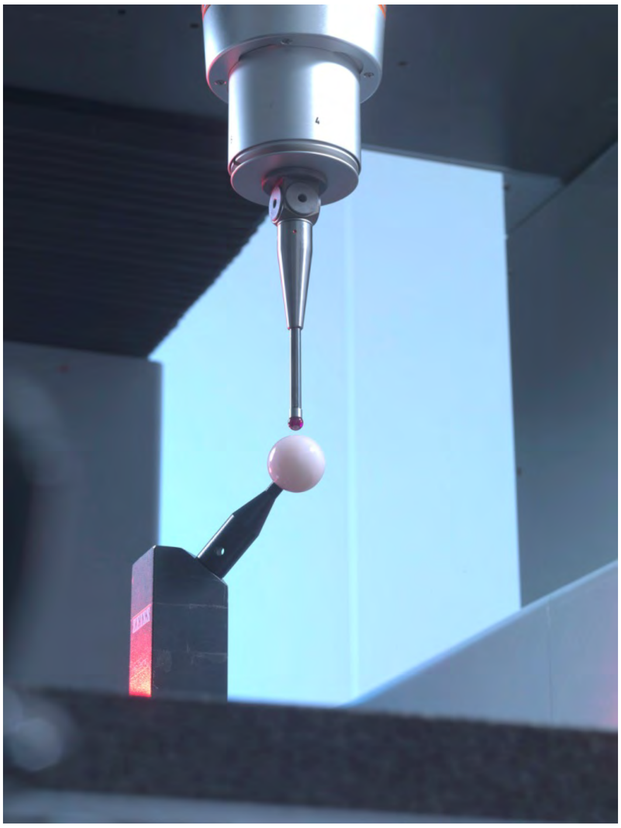


Figure 15 A photograph of the probe head shown in the exploded diagram left.

Microprobing systems

Conventional CMMs equipped with conventional probing systems are not suitable for measuring very small parts as the size of the stylus tip (> 1 mm) is usually too large and the static probing force (50 mN to 200 mN) is too high. In addition, the resolution of the probe is often not good enough. The dynamic probing force due to the high moving mass can also be an issue.

To overcome these limitations, commercial probing systems have been developed by Zeiss and XPRESS Precision Engineering based on probes with silicon membranes with integrated strain gauge sensors. These probing systems usually incorporate stylus tips with diameters of the order of 0.2 mm.

Other microprobes such as that developed at PTB and NIST are based on a spherical tip created on the end of an optical fibre. When the tip is displaced the amount and direction of displacement can be measured with a vision system. Probe diameters as small as 0.01 mm are possible with this system along with probing forces of the order of a few millinewtons. Its main disadvantage is that it does not allow axial probing so is essentially a 2D probe.

All microprobes are essentially 2.5D at best. In the case of the Zeiss microprobe the stylus and probe tip are integrated so a stylus change necessitates changing the whole probing system. The stylus can't be articulated and multi-stylus configurations are impossible.

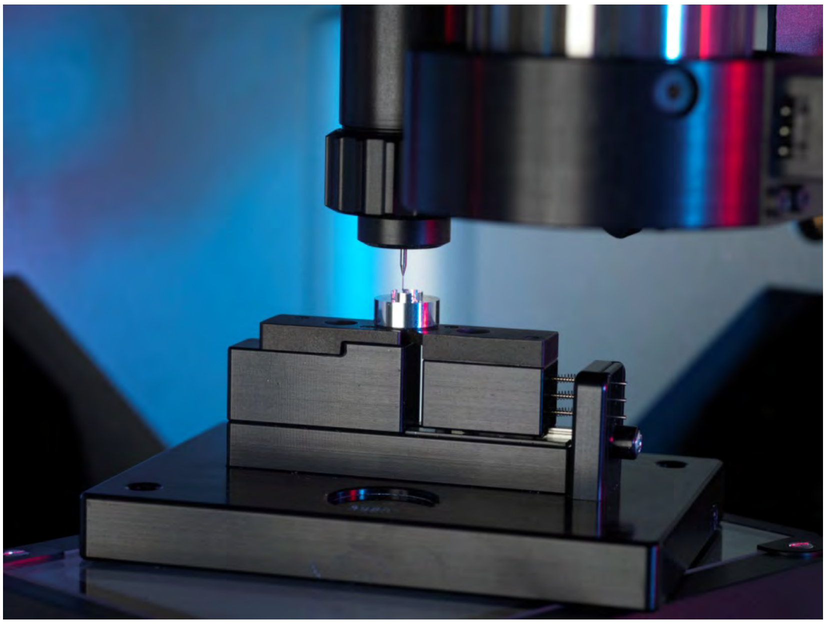


Figure 16 A micro-CMM probe. The stylus tip diameter is 0.125 mm.

Chapter Summary

- Understand the basic designs of analogue probes and how the differ from touch trigger probes.
- Be aware of microprobing systems.

Probing systems – an overview

4

IN THIS CHAPTER

- Workpiece related considerations
- Selection of probing system
- Probing system qualification

Both analogue and touch trigger probes have a stylus that makes contact with the workpiece being measured. Determining the number of points required to obtain an accurate measurement is dependent to a large degree on the skill and experience of the user, although semi-automated systems based on uncertainty estimating software are under development. Users requiring guidance on this subject are recommended to refer to NPL Good Practice Guide No. 41 *CMM Measurement Strategies*.

Summarised below are the key factors to be considered by the user, before measurement takes place.

Workpiece related considerations

The measuring procedure for the selected workpiece needs to be determined before commencing measurement. The obvious consideration is that the working envelope of the CMM should be large enough for the workpiece and includes enough free space to allow movement of the chosen stylus around the workpiece without risk of collision. The stylus should be able to access all features requiring measurement. Consideration should be given to the target uncertainty required for the measurement (usually 20 % of the smallest drawing tolerance or apply ISO 14253 rules using the task-specific measurement uncertainty). There is nothing to be gained by trying to achieve the most accurate result if the drawing tolerance does not warrant it.

Selection of probing system

A typical probing system may consist up to four elements: the probe head, probe extension, stylus adapter or extension and the stylus.

Probe head considerations

Types of probe head available may include articulated (manual or motorised) and, non-articulated. Manually articulated probing heads will require intervention by the user and will cause the part program to be paused at the point at which articulation is required, this will extend the measurement time on a DCC machine and may affect the accuracy of the measurement. Select the probe head with regard to the target accuracy. Chapter 5 covers probe heads in more detail.

Probe extension selection (extension bars)

The probe extension selection (

Figure 21) will depend on the type of measurement required, the accuracy, the mass and length of the stylus and the rigidity of the attachment face of the stylus. Probe extensions fit between the probe head and the contact trigger probe. Chapter 5 covers probe extensions in detail.

Stylus selection considerations

There are two major considerations in the choice of stylus. Namely the requirement of the stylus to make contact, without interference, with all points on the workpiece to be measured and the maintenance of repeatability at the point of contact. Chapter 8 covers stylus selection in detail.

Stylus extension selection

Stylus extensions and adapters are available to facilitate the measurement of features that are difficult to reach. The accessories available include knuckles, five way stylus centres, plain extensions and M3/M2 and M5/M4 adapters that accommodate interchange of styli with different thread sizes. Note that using a stylus with a thread size smaller than that of the probe will reduce the probe accuracy due to the lower stylus stiffness. Using styli with a thread size larger than that of the probe may cause false triggers with touch trigger probes.

Chapter 6 covers stylus extensions in detail.

Probing system qualification

To maintain accuracy the stylus combination needs to be ‘calibrated’ or to use the correct term 'qualified'. This involves determining the radius of each stylus and the distance between the centres of each stylus. This process is usually achieved by contacting a calibrated reference sphere with each of the styli. The CMM software then determines the diameters of the probe ball tips and the distances between them. Chapter 8 covers Stylus/Probe qualification in detail.

Chapter Summary

This chapter is an introduction to the chapters that are about to follow.

Probe head selection

5

IN THIS CHAPTER

- Non-articulating probe heads
- Articulating probing systems
- Changing stylus/probe
- Use of probe extensions

Probe head selection can significantly affect the overall system performance. This chapter covers the selection of the probe head and looks at articulating and non-articulating probing systems. Listed below are a number of factors that need to be considered when choosing a probe head.

- The response speed of the probe system must be compatible with the CMM controller.
- Where possible use the same probe body for a complete measuring application.
- The probe body should be able to accommodate all styli used for the application.

In manual operation, a touch probe may be subjected to accidental abuse. It is possible that the user may vary the speed and force when bringing the stylus into contact with the workpiece, this variation may also result in an excessive amount of over travel. To avoid damage to the trigger mechanism probe heads designed for manual operation must therefore be more robust than probe bodies designed for DCC.

The choice of probe head can also significantly affect the overall system performance. Compromises may therefore have to be made in the selection of the probe head in order to satisfy all measurement requirements. For example, a probe head that is capable of carrying a heavy stylus will also have a high measuring force and a slow response speed. In addition, when selecting a probe head the user should be aware that the more sensitive probe heads need a better thermal operating environment. For best results, the user should monitor the local ambient temperature and compare against that specified for the particular probe head in use.

In addition to the amount of weight the probe head will support, and the trade-off between sensitivity and thermal operating environment, the user should also consider the use of an articulating or non-articulating head and if it should be manual or automatic.

The reader should also be aware of the performance tests specified in ISO 10360-5:2010 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM)—Part 5: CMMs using single and multiple-stylus contacting probing systems*. Knowledge of these tests will help you to interpret data in manufacturer's brochures and manuals.

Non-articulating probe heads

Non-articulating probe heads permit only one fixed probe head orientation, that is to say, straight down. Non-articulating probe heads are used extensively for measuring features machined or stamped into flat sheet metal or any parts that only need a straight down probe orientation. Use can be made of them on both manual and DCC machines.

Articulating probing systems

Articulating probing systems (figure 18) enable the operator to direct the probe in many different directions. Articulated probe heads control the direction that the probe points. The number of degrees of elevation in the vertical plane is controlled by the A-axis (figure 19) and the B-axis controls the direction that the probe points in the horizontal plane. The angles are usually in either 15 degree or 7.5-degree increments. This type of probe head allows the measurement of features on the back or sides of the workpiece as well as features at oblique angles.

Articulating probing systems come in two general varieties: manual (figure 17) and motorised (figure 18). Each articulating probe head has a maximum allowable extension length. If penetration into a deep bore is required, the user should ensure the use of a probe head that can support the weight of the required extension bar.

Figure 17 A manually articulating probe head (© Tesa Group)

Manually articulating probing systems require user intervention to move the probe to the desired orientation. These types of probe can be used on manual and DCC machines; however, on a DCC machine the program will pause at each programmed probe orientation point and wait for the user to articulate the head.

Figure 18 Renishaw type PH1 and PH5 probe heads (© Renishaw plc 2002)

With manually articulating probing systems, once the required position has been selected the new stylus position will require qualification against the reference sphere. It should be noted that the heat generated by the user when orientating the probe may cause errors in the recorded results due to thermal expansion of the stylus. Therefore, it is advisable to wear gloves when orientating the probe.

With some types of manually articulating probing systems a number of qualifications using a reference sphere can be performed with the probe set in a number of positions. During measurement, the user may re-orientate the probe head to one of the positions previously qualified and measurement can then take place without further checking against the reference sphere. Other manually articulating probing systems require qualification with a reference sphere directly after each re-orientation of the head. It is important, when using this type of probe head, that no movement of the reference sphere occurs during qualification as this will lead to errors in the measurement results, due to qualification errors.

Automatic or motorised probing systems (figure 19) allow automatic changing of the probe angles from within the part program. Therefore, very complex part programs utilising many different probe positions can be run completely unattended. These probe heads are used only on automated CMMs. The same qualification procedures described for manually articulating probing systems are also required for automatic or motorised probing systems.

If the user employs a Direct Computer Control machine and only requires articulation of the probe head occasionally then the use of a manually articulating probe head is recommended. If, however, the measurement strategy requires articulation on a regular basis then an automatic articulating probe head is required. This type of probe head will allow the user to gain full benefit from the part program and will avoid constant pauses in the machine cycle in order for the user to re-orientate the probe head manually. A part program is of little benefit if the user is required to stand by the machine during the part program cycle and change probe orientations on a frequent basis.

Figure 19 A Renishaw PH10M indexable motorised head (© Renishaw plc 2006)

Section 6.4 of ISO 10360-5 covers the verification of articulating probing systems. The principle of the test is to measure the form, size and location of a test sphere using five different angular positions of an articulating probing system. At each angular position, 25 points are measured on the test sphere, for a total of 125 points using all five positions. The ranges of the centre of all five spheres are calculated. The largest of these three ranges yields the probing-system location value. In addition, a least-squares sphere fit using all 125 points is examined for the form and size errors of indication. This analysis yields the multi-stylus size error and multi-stylus form error.

Changing stylus/probe

Probe accuracy depends on the triggering system design. The strain gauge type is more accurate than the simpler touch-trigger probe designs, especially when used with a long stylus.

When designing a measurement strategy it is good practice to consider the system’s ability to change the stylus tip automatically within a part program. Requalification of the stylus tip before use will always be required with those probe heads where the styli removal is by unscrewing from the probe and attaching a replacement.

Some stylus modules are attached magnetically to the probe. Remove and replace these modules either by hand or by the use of a module changing rack. It is recommended that, in order to maintain accuracy; after the stylus module change has been completed, the stylus should be requalified before further measurement takes place. This is particularly important if the temperature in the room has changed since the last qualification.

Using an autochange rack (figure 20) allows automatic stylus tip change within a part program with no operator intervention being required.

Figure 20 An autochange rack (© Tesa Group)

Note that ISO 10360-5 contains information on verification when a stylus- or probe-changing system is supplied with a CMM and is covered in a later chapter.

Use of probe extensions

Probe extensions extend the reach of probes (figure 21 and figure 22). They are a series of probe extensions placed between the probe and probe head to provide increased reach with minimal loss of accuracy.

The user should keep the probe extension length to a minimum. It should be just long enough to allow the stylus to always make contact with the workpiece during the complete measurement process.

Manufacturers of probe heads and accessories generally specify maximum recommended lengths for probe extensions. Using extensions that exceed these lengths may seriously affect the accuracy and repeatability of the probe head readings.

As an example Renishaw recommend a maximum extension bar length of 200 mm for their motorised probe head, PH9.

Figure 21 An extension bar kit © Renishaw plc 2014

Figure 22 An extension bar in use. © Tesa Group

Chapter summary

- Be aware of the types of articulating probe head, both manually articulating and motorised.
- Be aware of good practice when using probe head extension bars.

Selection of stylus type

6

IN THIS CHAPTER

- Keep the stylus simple
- Keep the stylus short and stiff
- Select a large ball tip
- Check the stylus tip
- Keep the stylus tip clean
- Types of stylus tip
- Selection of stylus extensions knuckles and adaptors

Stylus tips make contact with the workpiece. They generally consist of synthetic mono crystalline highly spherical industrial rubies (Al_2O_3) mounted on a shaft. Ruby is a hard ceramic material ensuring minimum wear of the stylus ball. There are numerous types and sizes available for a variety of applications; the shafts on which the styli are mounted are usually non-magnetic stainless steel, ceramic, carbon fibre or tungsten carbide.

Ruby ball styli are suitable for the majority of probing applications. To maximise the accuracy of measurements taken, the user should follow the following rules:

- keep the stylus configuration simple;
- use a short stiff stylus;
- use the largest ball tip possible;
- check that the stylus tip has not come loose from the stem;
- keep it clean; and
- use the most appropriate stylus type.

Keep the stylus simple

To maintain accuracy of measurement the user should keep the stylus system as simple as possible, a single straight stylus will generally give better performance than a stylus with bends and joints. Therefore, whenever possible the user should choose an articulating or indexing probe head with a straight, rather than a compound stylus.

Keep the stylus short and stiff

Ensure that the stylus is short and stiff, the more the stylus bends the lower the accuracy. If it is necessary, for a particular measuring task, to use a long stylus offset or extension then it is also necessary to use a high accuracy probe head. In such cases, the user should perform a test on a known artefact to verify that the required performance is achievable. Clause 8.3 of ISO 10360-5:2010 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM). CMMs using single and multiple stylus contacting probing systems* gives further information. The points noted in Annex C should also be observed.

Select a large ball tip

The stylus tip diameter should be as large as possible. With larger diameter stylus tips, surface finish has less effect on the measurement you will gain more flexibility due to the larger ball/stem clearance. The smallest diameter hole requiring measurement dictates the largest useable stylus tip. Each stylus has an Effective Working Length (EWL). This is the penetration achieved by the ball before the shaft fouls on the component. Usually the larger the ball the greater is the EWL (see figure 23).

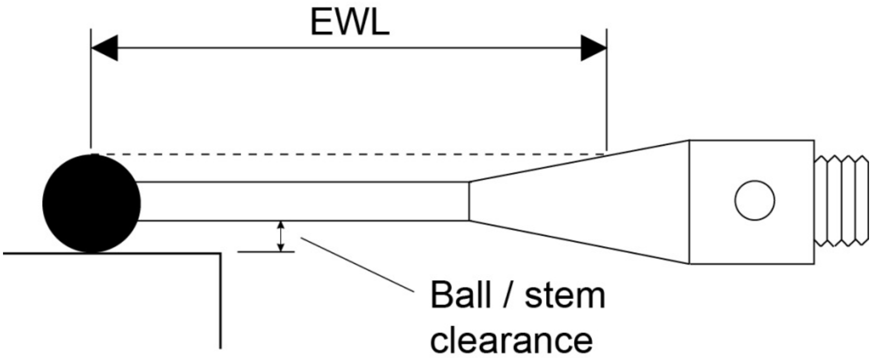


Figure 23 Effective Working Length (© Renishaw plc 1987)

Check the stylus tip

The stylus tip can eventually work loose. This is particularly the case if the probe has been in collision with the workpiece. Before any measurement, check that all stylus tips are firmly attached to their shafts. A loose tip could cause inaccurate and variable results and poor qualification data. A tip that falls off may result in damage to the workpiece.

Keep the stylus tip clean

It is good practice to clean stylus tips regularly. A tip left on the machine inactive overnight can pick up dust. Even in a nominally clean environment, the stylus tip can pick up fibres of dust from clothes *etc*. If the component has not been cleaned properly the stylus could pick up dirt from the previous component measured. Clean the tips with a fine brush prior to qualification and check the tips for fingerprints. Remove all marks and dust prior to qualifying the probe. Extra cleaning may be needed in workshop environments.

Types of stylus tip

In addition to the normal stylus tips associated with CMMs there are some applications that require the use of specialised stylus tips. This section covers some of the more common specialised stylus tips.

Star stylus

For measuring hole diameters, undercuts, grooves and concentricity a star stylus (figure 24) should be used. Star styli can also be used to inspect extreme points of internal features such as the sides or grooves in a bore. This type of stylus minimises the need to move the probe due to its multi-tip probing capability.

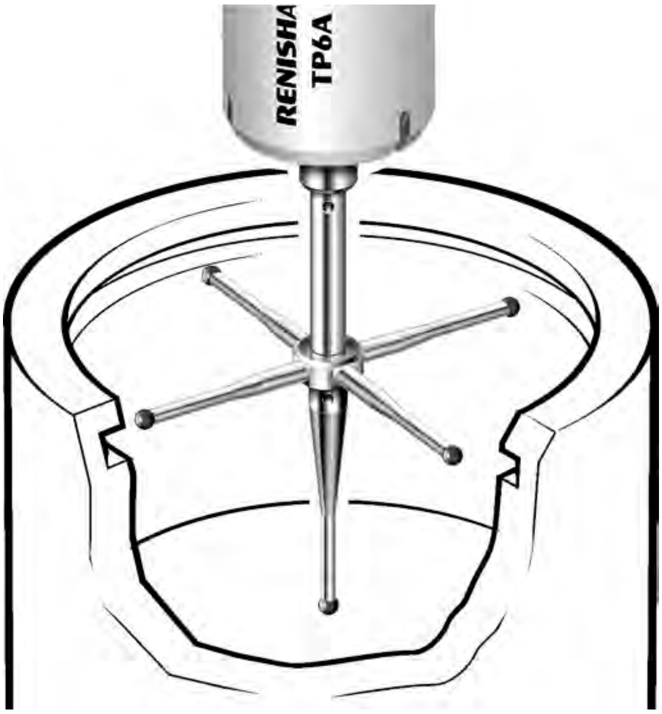


Figure 24 Star styli (© Renishaw plc 2014)

Disc stylus

Where the feature is too small for easy access of the star stylus then a disc stylus (figure 25) can be used. A simple disc stylus requires qualifying on only one diameter using a ring gauge, this limits effective probing to X and Y directions only.

The edge of the disc has a spherical shape and, because only a small region of the spherical surface is available for contact, thin discs require careful angular alignment to ensure correct contact between the disc surface and the probed features.

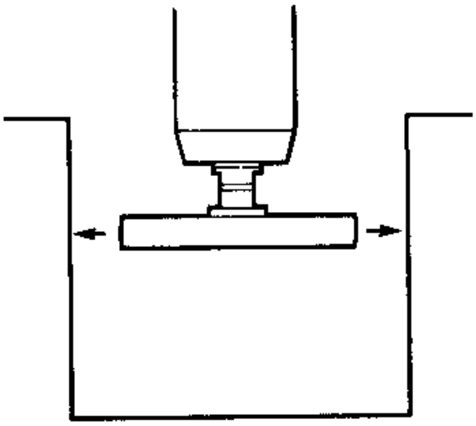


Figure 25 Disc styli

Figure 26 A disc stylus in use (© Renishaw plc 2014)

Other special styli

Special styli are available for applications that are unsuitable for standard probing. Cylinder shaped styli (figure 27) of various diameters can be used for measuring threads, locating centres of tapped holes and plain holes in sheet metal (figure 28).

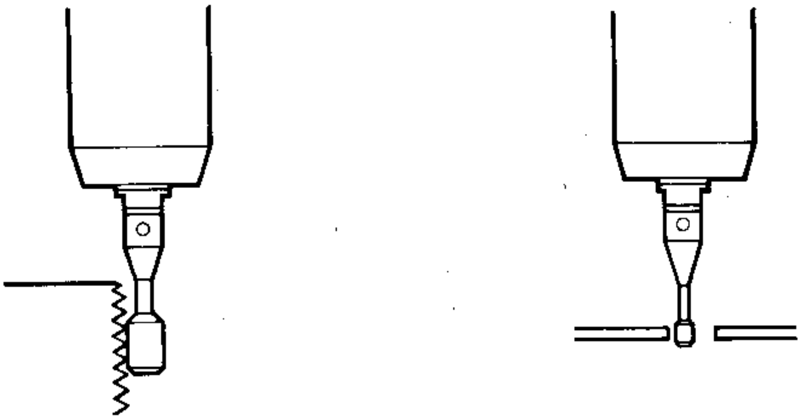


Figure 27 Cylinder styli probing a thread and a thin sheet

Figure 28 A cylinder stylus in use (© Renishaw plc 2014)

A large hollow ceramic ball (figure 29) can be used for probing deep features in X, Y and Z directions. Probing with large diameter balls can average out the effects of rough surfaces.

Figure 29 Ceramic hollow ball styli (© Renishaw plc 2007)

Use a pointed stylus (figure 30) to inspect points, scribed lines and thread depths. The use of a radius-end pointer stylus allows more accurate datuming and probing of features and can be used to inspect the location of small holes.

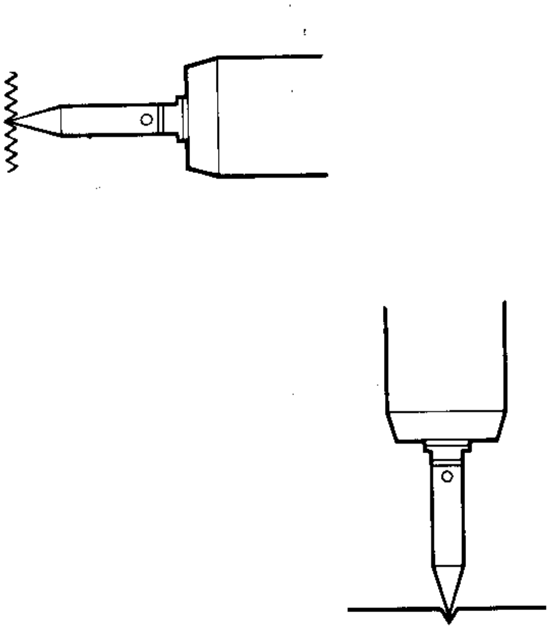


Figure 30 Pointer Styli

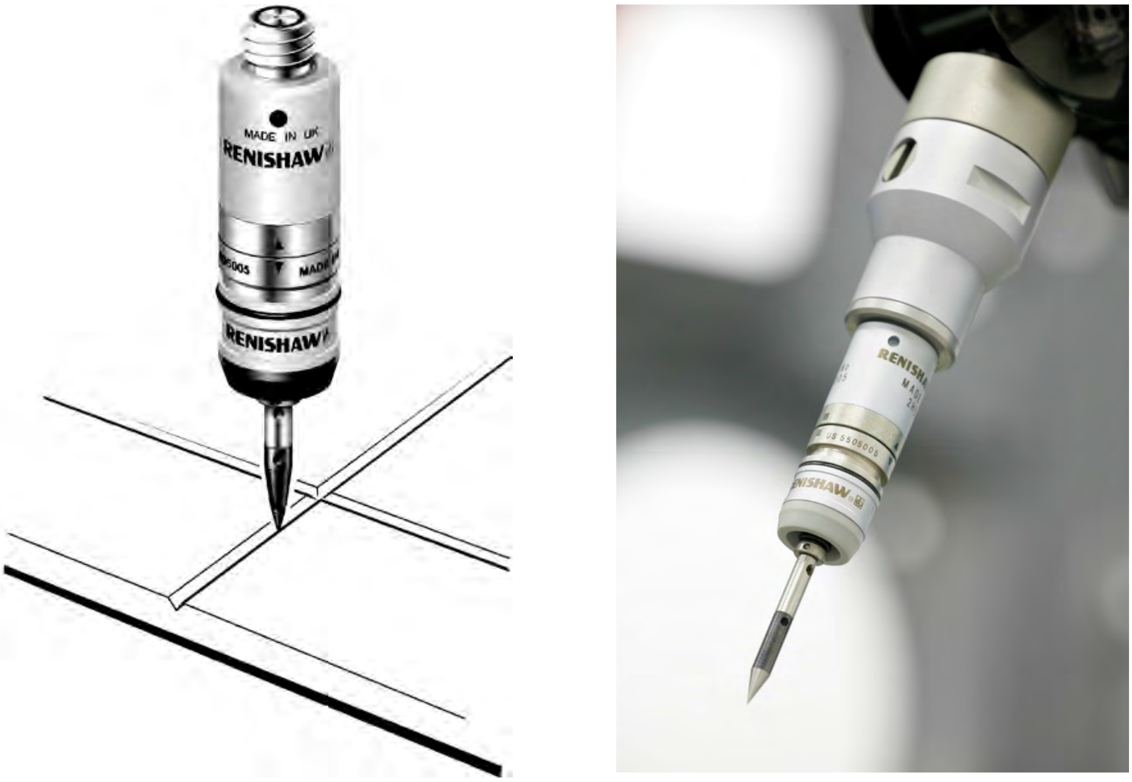


Figure 31 An application of a pointer stylus (© Renishaw plc 2014)

A stylus centre (figure 32) allows maximum probing flexibility, using a single probe taking up to five styli, and can be configured to the user's specification. Various sizes of centre block are available and each stylus can have a different length and tip diameter as required. The user should take care to ensure that the mass of the stylus is not excessive as this may exert an out-of-balance force on the probe mechanism. This type of stylus can reduce cycle times by avoiding the need to change the stylus during the measurement cycle.

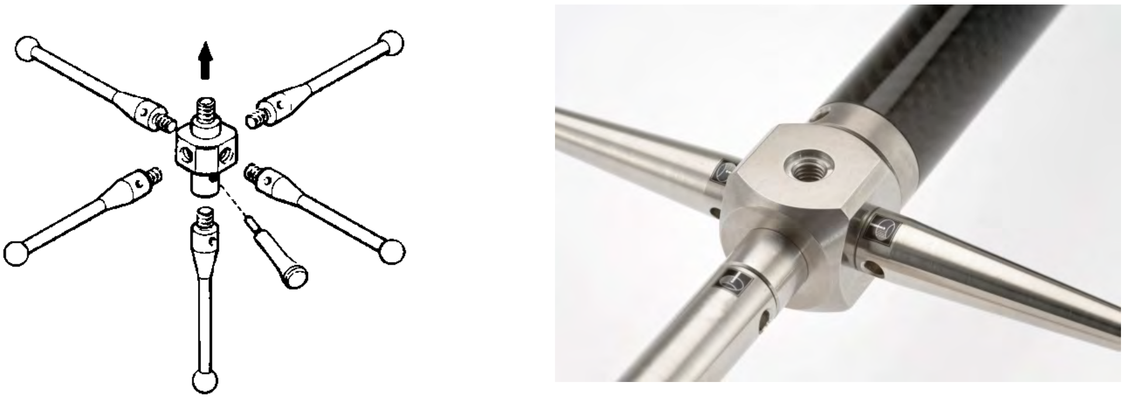


Figure 32 A five-way stylus centre (©Renishaw plc 2007)

Selection of stylus extensions knuckles and adaptors

To facilitate the measurement of features that are difficult to reach, knuckles, adapters and stylus extensions are available.

Stylus knuckle adaptor

The stylus knuckle adapter (figure 33 and figure 34) can be used for probing angled features when access is not a problem. The adaptor can be orientated in both the vertical and horizontal planes. This accessory is useful when the probe head cannot be used to correctly orientate the probe.

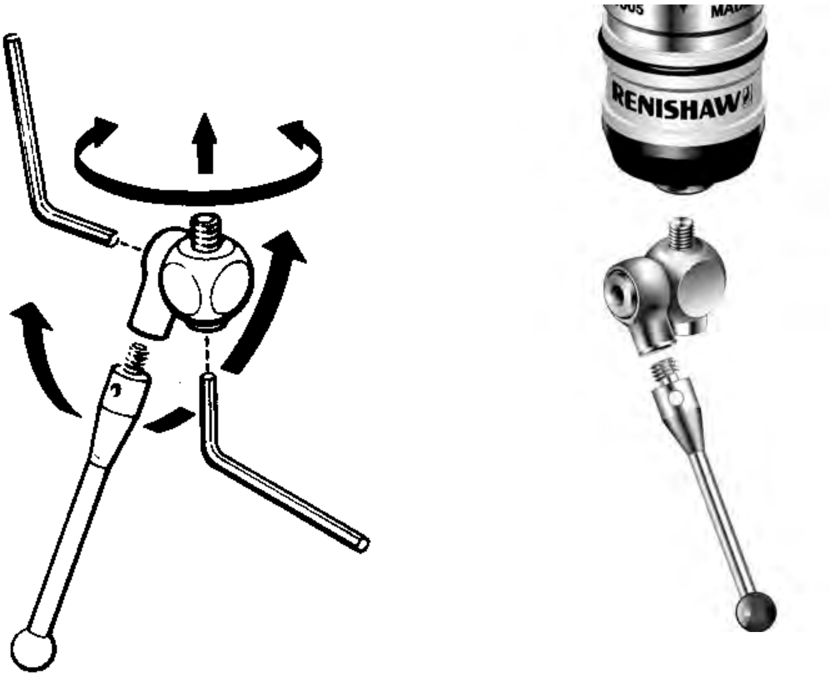


Figure 33 Stylus knuckle (©Renishaw plc 2007)

Figure 34 Stylus knuckle (©Renishaw plc 2007)

Stylus adapter selection

Stylus adapters (figure 35) allow the use of all styli on all touch trigger probes. The user should, however, be aware that using, for example, an M2 thread stylus on an M3 thread probe would normally reduce the stylus stiffness resulting in a reduction of probe accuracy. In addition, using styli with a thread size larger than that of the probe may cause false triggers.

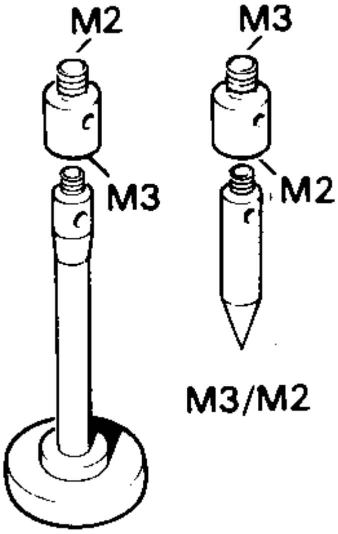


Figure 35 Stylus Adaptors (© Renishaw plc 2014)

Use of stylus extensions

Stylus extensions (figure 36) provide added probing penetration by extending the stylus away from the probe. The use of stylus extensions will reduce probe accuracy due to the loss of rigidity and susceptibility to temperature changes. A steel 100 mm extension will change length by 0.001 mm for each 1 °C change in temperature.

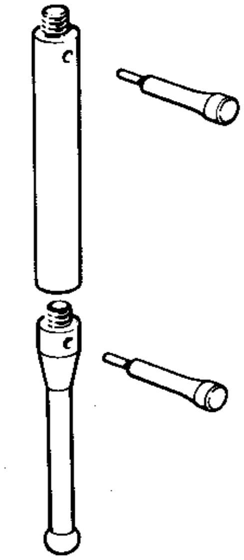


Figure 36 Stylus extensions (© Renishaw plc 2014)

It is always important with any kind of adaptor to make sure all the joints are tight before making measurements.

Chapter Summary

- Keep the stylus configuration simple.
- Use a short stiff stylus.
- Use the largest ball tip possible.
- Check that the stylus tip has not come loose from the stem.
- Keep it clean.
- Use the most appropriate stylus type.

Touch probe operation

7

IN THIS CHAPTER

- Contact force (the gram gauge)
- Approach velocity
- Workpiece deformation
- Cleanliness of the work area
- Stylus shaft contact
- Chapter summary

This chapter will give an overview of some of the considerations when using a touch trigger probe.

Contact force (the gram gauge)

The probing force of a mechanical kinematic touch trigger probe can be adjusted by turning a screw that compresses a spring in the probe body. This is an important adjustment since probing errors will reduce linearly with decreasing probe force. However, the force should not be reduced so much that false triggers occur. If adjustments of this nature are made, it is essential to requalify the probe and stylus.

With some probes, changes in stylus length or the use of extensions will alter the contact force required to trigger the probe head. This is due to the lever effect. The shorter the stylus the higher the force required to trigger the mechanism. Manufacturers of probing systems provide a gram gauge (figure 37) for the adjustment, resetting and checking of probe trigger forces. Correct use of the gauge in setting the optimum trigger force maximises probe performance. The typical gauge can be used to set trigger force settings in the range 4 grams to 35 grams and the graduations are set at 1 gram intervals, sufficient for all probe trigger force measurements. The manufacturer of the probe will normally specify optimum trigger forces for various combinations of probes and stylus length.

Figure 37 A gram gauge (© Renishaw plc 2011)

Approach velocity

A slow approach velocity will ensure high accuracy; the use of the same approach velocity for all measurements will ensure high precision readings. The final approach velocity is usually under the control of the machine software system and cannot always be adjusted by the user.

It is good practice that the approach velocity used for the qualification of the probe is the same as that used during the measurements and that the force and direction of the approach are maintained in accordance with the procedure used for probe qualification.

Workpiece deformation

At the contact point, a force will occur between the stylus and the workpiece. If the component being measured is not robust and therefore likely to deform then a non-contact probe needs to be considered. Typical non-contact probes available use video and laser technologies (see chapter on Non-contact probing systems).

Some CMM software has special measuring force extrapolation functions. Measurements are made at two measuring forces and the results extrapolated to zero force. This software is used for measuring elastic workpieces[2].

Cleanliness of the work area

It is essential to maintain the cleanliness of the work area. Swarf, dust and dirt at the contact points can give inaccurate results, and can cause wear to the stylus tip. It is, therefore, important that both the workpiece and stylus tip are cleaned before measurement. Either dust the stylus tip with a clean soft brush or wipe with a lint free cloth. It is also important that the reference sphere is clean. Again, a soft brush or a lint free cloth may be used. The component to be measured should be cleaned with a suitable solvent to remove all traces of oil, grease, dirt and fingerprints.

Stylus shaft contact

The CMM software is programmed to compensate for the diameter of the stylus, if the stylus shaft comes into contact with the workpiece rather than the tip then an inaccurate reading will be registered. It is important that when programming the CMM to make a pre-measurement run to check that the stylus shaft will not collide with the workpiece (figure 38). This alignment is particularly important with long styluses as a small angular error can result in large displacements at the stylus tip.

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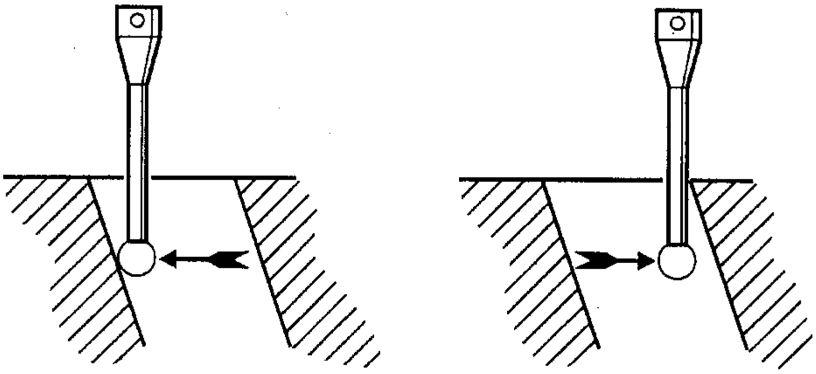
[2] Note that it may not be possible to control the maximum force that is applied – use of small diameter stylus tips on 'soft' materials may lead to plastic deformation (indenting).



Satisfactory contact

Contact not satisfactory

Figure 38 Contact on stylus tip not on the stylus shaft (© D.R.Coleman & T.F.Waters)

Chapter summary

- Use a suitable probing force – check with gram gauge.
- Use the most appropriate approach velocity.
- Keep the stylus tip and calibration sphere clean.
- Check that the stylus stem does not contact the workpiece.

Probing system qualification

8

IN THIS CHAPTER

- Probing system qualification
- Monitoring qualification
- Chapter summary

The most common type of touch trigger probe is based on a mechanical kinematic triggering mechanism. The touch trigger probe suffers from large systematic errors that depend on the probe approach direction as we saw in chapter 2. These errors are reduced by software correction implemented by the CMM manufacturer. For information on a method of software correction implemented by NIST see ‘NIST Model Boosts CMM Accuracy’, Quality Online, April 1998 and ‘Error compensation for CMM touch trigger probes’ W. Tyler Estler *et al. Precision Engineering* **19**:85-97, 1996.

Probing system qualification

Once the probing system has been selected it will need to be qualified using a reference sphere or other known standard (figure 39) since all probings must be corrected for the stylus tip diameter. It is possible to use gauge blocks and plain setting rings in order to qualify the stylus. However, the sphere is the preferred choice since all probing directions are taken into account. Qualification involves determining the diameters of the stylus tips and the distances between them. This effectively creates an imaginary probing sphere of zero dimensions that can access any point. Note that the effective diameter of the stylus sphere is always smaller than its actual size as it takes into account bending of the shank.

It is very important that the correct reference sphere is used and that entered into the software is its latest calibrated size. It is also essential that the stylus tip and qualification artefacts are scrupulously clean. The smallest amount of dust can lead to an incorrect probing system qualification. Both stylus and reference sphere should be cleaned with a soft brush. Examine the reference sphere under a magnifying glass for signs of fingerprints or dust and remove any contamination.

To achieve accurate and consistent measurements, the user should, where possible, aim to replicate the conditions under which the measurement will take place during the probing system qualification procedure. For example, the direction of approach of the stylus to the artefact should ideally be the same as the direction of approach used when measuring the workpiece. Probing force and probing speed should also be kept constant.

For reliable qualification twenty-five to fifty touch points are recommended for each stylus tip. (Reference Quality Magazine April 1999: *Improve the Performance of Touch Trigger Probes*; Phillips and Estler).

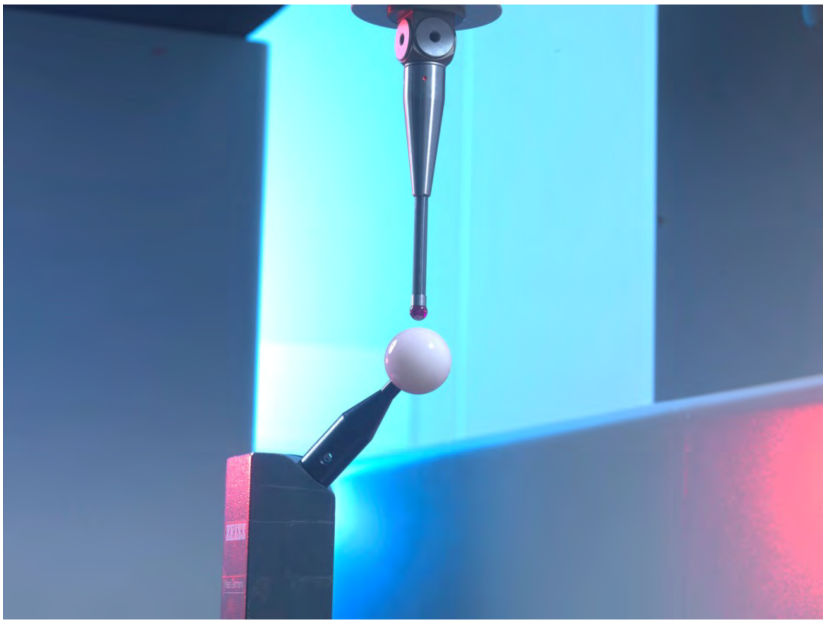


Figure 39 Stylus qualification

Although careful qualification of the stylus will not directly reduce the errors inherent in the probe design, it will improve the accuracy of some measurements, such as features of size. For example, when determining say the distance between two spheres or two holes the calculation of the location of the centres is unaffected by any error in the stylus tip radius. However, when measuring a feature of size, such as the length between two faces or the diameter of a hole, the radius of the stylus tip will have an effect since it is used in the calculation of the feature size. By increasing the number points used in the stylus tip qualification, the resulting effective stylus tip diameter will be more accurate. To maintain the full benefit of improved qualification, the workpiece feature under measurement must also be measured with an increased number of points. As stated earlier, benefit will be gained from using 25 to 50 points per tip qualification.

It is recommended that for small diameter styli a small diameter reference sphere should be used, for example, for qualification 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 relates to the sphere in use. A common error is entering the wrong value for the reference sphere in use into the CMM software. If this happens then the qualification output will be incorrect. It should also be noted that if an ISO 10360:2 verification has been performed on the machine then that machine is only verified for measurements made using the same reference sphere as used for the verification test. It is advisable, wherever possible, to only use the reference sphere supplied with the machine.

Monitoring qualification

Keep a written record of the qualification constants for the stylus for future reference. Ideally, if the same probe is used regularly its qualification constants should be monitored. At the very least record the effective diameter of the probe tip. Some CMM software gives an indication of the deviations of the probed points from a true sphere. The user should check that these deviations are within the normal expected range. Remember if the probe qualification is incorrect all future measurements made until the next qualification will be incorrect. Ask the following question.

Does this probe normally output this value, if not why has the value changed?

If the qualification values have altered significantly then the user should take action to investigate the reason why. Make sure that the stylus and reference sphere are clean, that the value entered into the software corresponds to the reference sphere currently being used and that the probing strategy is the same as that used previously.

Measuring the length of a known artefact, for example, a calibrated gauge block or plain setting ring is a simple check on the probe qualification. If the difference between the calibrated size of the gauge block and the length you measure is not within the machine's specification at this length, then requalify the probe and repeat the check.

Chapter summary

To summarise, the key steps in the probe qualification procedure are listed below.

- Clean stylus and calibration sphere and check that it is adequately clamped.
- Check correct calibration sphere diameter is entered into the software (check against latest calibration certificate).
- Calibrate styli using a probing strategy that matches the probing directions on the workpiece. At the very minimum, probe two points close to the pole and four points on the equator. Use automatic calibration routines if available.
- Check that sensible values have been recorded - keep all printouts.
- Check against any history.
- Measure a known artefact before measuring the workpiece.

Sources of uncertainty of measurement

9

IN THIS CHAPTER

- Elastic deformation of the stylus stem
- Probing strategies
- Summary
- Thermal expansion

A machined workpiece is a combination of standard geometric shapes such as flat planes, circles, straight lines, cylinders, cones and spheres. The geometry of a feature is measured using a number of contact points. The choice of the number and location of these points is crucial to the validity of the measurements. NPL Good Practice Guide No. 41 *CMM Measurement Strategies* gives guidance on the choice of number and location of the probing points. This section describes some of the sources of measurement uncertainty introduced by the selection of both probe and stylus system.

Elastic deformation of the stylus stem

The stylus stem is in effect a cantilever in that one end is built into the probe head and a force acts at the other end (the tip) of the stylus. This force will induce stress in the stylus shaft, causing it to bend. Therefore, take care in stylus selection.

Thick styli

Stylus bending depends inversely on the fourth power of the stylus shaft diameter. Using a stylus shaft with twice the diameter could therefore reduce probe errors by a factor of sixteen. It is therefore advisable to use the largest ball diameter that allows the stylus to enter the smallest internal feature. This keeps the shaft diameter as large as possible.

Short styli

The errors of kinematic touch trigger probes increase quadratically with stylus length. (The stylus bending increases with the cube of the stylus length, but the force required to trigger the probe decreases linearly with stylus length, hence the quadratic effect.) This assumes that the styli have the same cross-sectional area. Experimental data confirming the quadratic dependence of mean pre-travel on stylus can be found in *Error compensation for CMM touch trigger probes* by W. Tyler Estler *et al*.

The user should therefore choose the stylus that is just long enough to measure the workpiece. Use the shortest stylus that allows access to all the features that you want to probe. If it is possible, reducing the stylus length by half reduces the probing errors by a factor of four.

Stiffness of styli material

A stylus made of a stiff material will resist bending; a doubling of the stiffness will reduce the stylus bending by half. However, problems can arise due to stiff materials having higher densities, which increase the mass of the stylus. This extra mass can result in false probe triggering due to the inertial mass of the stylus during the acceleration phase of the CMM motion.

In the selection of probe materials manufacturers normally compromise by using the specific stiffness of the material (table 1), this value is the ratio of the material’s modulus of elasticity to its density.

Table 1 Typical stiffness properties of materials

Typical stiffness properties of materials				
	Stainless steel	**Graphite**	**Tungsten carbide**	**Ceramic**
Stiffness (GPa)	200	100	600	380
Specific stiffness	25	54	40	95

The above table shows, for instance, that tungsten carbide is very stiff but its specific stiffness is low because it is very heavy (dense). Ceramic on the other hand has a high specific stiffness because it is light and stiff. The best material (not shown in the table) is carbon fibre as it is lighter and stiffer than ceramic. The limitation of carbon fibre is that shafts made from it have to be at least 3 mm in diameter. Steel is the poorest material as it is too heavy and not stiff enough for long styli.

An experiment

The effect of some of the above factors on a measurement can be difficult to quantify in general terms. However, the effect can be determined experimentally in the following manner:

Mount a known artefact on the machine, for example, a calibrated gauge block or plain setting ring. Measure the artefact using a number of commonly used stylus and probe configurations. Examine the variations in the measured sizes and, in the case of a ring gauge, the position of the centre of the ring. Compare the differences of the measured size using each stylus with the known size to give the user an indication of the increase in error associated with each stylus type.

Probing strategies

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 following is a number of parameters listed according to their influence on the accuracy of a CMM fitted with a touch trigger probe.

- The length of the stylus stem.
- The cross sectional area of the stylus stem.
- The approach distance to the surface.
- The speed of approach to the surface.
- The direction of approach to the surface.
- The mounting of the stylus stem.
- The orientation of the workpiece.
- The location of the workpiece.
- The probing force on the surface.
- The return spring pressure within the probe.
- The mechanical properties of the stylus shaft.
- The form of the stylus tip (sphericity).
- Contact condition (particularly contamination).

These parameters were investigated and reported in *Some performance characteristics of a multi-axis touch trigger probe* by F M M Chan *et al.* (1997). Some of these effects will also apply to analogue probes. The following is a summary of some of the findings of this investigation.

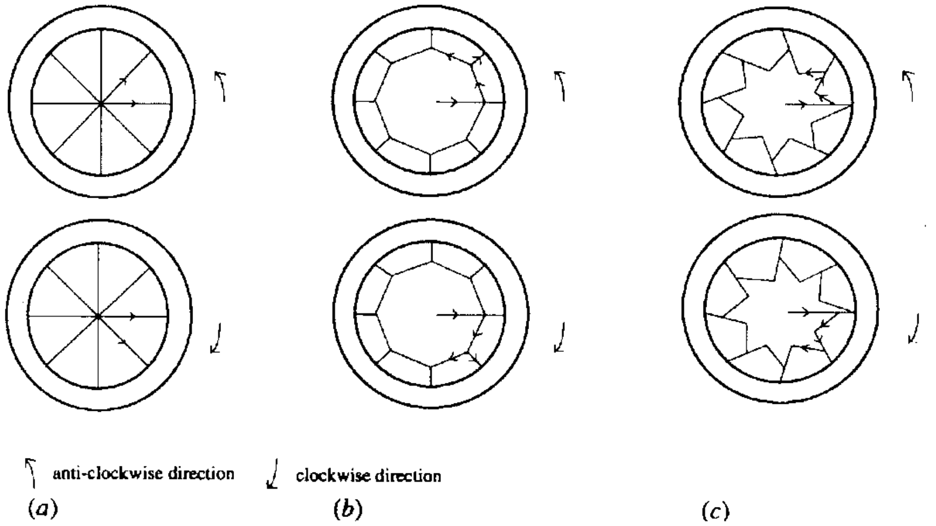
The effects of stylus length and diameter

Results of tests on styli of various lengths and diameters made it clear that long styli should be avoided whenever possible. Long styli were found to bend more than shorter styli on surface contact, due to the reduced stiffness. When a long stylus is used in a horizontal position an additional bending displacement (gravitational sag) causes the stylus and probe mechanism to bend further. When measuring deep bores, the user must compromise by using a long stylus but should be aware of the potential errors that can be generated. It is good practice to counter weight a long stylus but be careful you don't exceed the total load carrying capability of the probe head.

Styli of small shaft cross section (dictated by ball size) tend to be influenced by the imperfections of the workpiece surface. If the radius of the stylus tip is smaller in diameter than the feed of the cutting tool used to produce the workpiece then significant errors can result in the measured readings. In addition, when a small stylus is used whose diameter is only a little larger than the stylus stem there is a risk of the shaft touching the surface ahead of the contact by the ball.

The effect of the direction of approach

Three alternative patterns of approach were examined for the probing of a circular feature, radial, circular and saw tooth (figure 40).



Alternative patterns of probe movement: (a) radial, (b) circular and (c) saw-tooth.

Figure 40 Alternative patterns of probe movement (F M Chan *et al*)

All of the patterns were tested both in the clockwise and in the anti-clockwise direction. The results obtained using the saw tooth pattern indicated considerable variability in both directions furthermore the variability of results produced using this pattern was larger than those for the radial and circular patterns.

The results also indicated that there are no differences in the performance between the radial and the circular patterns when they were measured in the clockwise and the anti-clockwise directions respectively. However, when a number of tests were performed to compare the behaviour of the two approach movements significant differences were found. **The results confirmed the radial method to be the best path for measurement.**

The effect of approach distance.

To determine the effects of the approach distance a number of distances were tested. The approach distance is the span from the instant the speed changes from fast to slow before contacting the surface. The CMM carriages are excited by the vibrations (acceleration and fluctuating forces) and as result a settling period is required after a change of speed. The settling period is usually specified by the CMM manufacturer.

The larger approach distances gave smaller positional variations since they allowed the probe to attain a stable state. Thus, mechanical oscillation was damped out prior to probe triggering. For example using a 24 mm approach distance halved the errors when compared to a 6 mm approach for the particular machine tested. In practice, a compromise must be made between speed and accuracy. Again the user is advised to perform experiments to determine the most appropriate approach distances for their measurement set up.

The effect of measuring speed

A component was measured over a range of speeds to determine the optimum range of measuring speeds (also known as speed of approach). Here it was found that a comprise must be made between very slow speeds, which result in an unreasonably long time being required for the user to complete the measurements, and fast speeds that result in large impact forces on surface contact.

It was observed that at slow measuring speeds the errors were large but consistent, due to the amount of time required by the slow speed to trigger the probe.

At fast measuring speeds, the probe triggers in a shorter time and the deflection of the stylus is significantly reduced. However, with fast measuring speeds larger forces are produced on contact and these have a greater effect on the component being measured and cause vibration and inertia effects. The results illustrate that a fast measuring speed of 111 mm s^{-1} with a moderate feed of 83 mm s^{-1} gave the least error for the particular machine used for the test. It is suggested that the user perform tests to ascertain the effect of measuring speed in their own measurement set-up.

Effects of location of workpiece and mounting of the stylus

To determine the effects of varying the location of the workpiece and hence the mounting of the stylus stem a ring gauge was measured in five different locations. In each case the axis of the ring gauge and the stylus assembly were parallel to one of the machine axes. The measured results obtained by Chan showed least variability at the centre table location in the XY plane, making this the appropriate location for taking measurements. The stylus should be orientated along the vertical axis whenever possible.

Summary

All of the above demonstrate clearly that the user can either introduce or conversely minimise the errors of probe measuring systems by the adoption of varying measuring strategies.

As a rule of thumb, when choosing a stylus the points below should be observed.

- To keep the stiffness high minimise the number of joints in the stylus assembly.
- Use the shortest stylus possible.
- Use the largest diameter stylus ball possible.
- Avoid handling the stylus unnecessarily - use gloves when handling long stylus combinations.

Most of the points listed above apply equally to both analogue and touch trigger probes.

Thermal expansion

Styli are a potential source of thermal expansion error. This can result, for example, from handling of the probe body and stylus during attachment to the machine or when changing the orientation of a manual articulating probe head.

To give an indication of the effect of temperature, an 8 mm diameter probe tip (typical thermal expansion coefficient 5×10^{-6} °C^{-1}) experiencing a change of temperature of 3 °C will change in diameter by

$$5 \times 10^{-6} \times 8 \times 3 = 0.000\,1 \text{ mm}$$

This change is significant on some of the higher accuracy machines on the market.

A more important change is the change in length of the stylus shaft. For a steel shaft 100 mm long (typical thermal expansion coefficient 12×10^{-6} °C^{-1}) the change in length for the same temperature change of 3 °C is

$$12 \times 10^{-6} \times 100 \times 3 = 0.003\,6 \text{ mm}$$

In addition, if two of the stylus tips on a t-shaped probe are 100 mm apart there will be an apparent shift between measurements made on the position of the same feature using each of the styli.

It is, therefore, necessary to allow a stylus to reach thermal equilibrium with the environment before stylus tip qualification. This can take from several minutes to an hour, depending on the accuracy needed and the size of the stylus. You can shorten this time by using gloves when inserting stylus systems in to the probe head or probe changing rack.

If the environment is also subject to temperature fluctuations it is necessary to requalify at frequent intervals.

Chapter summary

- Be aware of the thermal implications when assembling stylus configurations.
- Be aware of how to choose the most appropriate stylus.
- Be aware of the effect of measurement strategy with regards to direction of approach and measuring speed on the results.

Continuous scanning

10

IN THIS CHAPTER

- Open loop scanning
- Closed loop scanning
- Continuous scanning probes
- Choice of scanning styli

Conventional CMMs equipped with touch trigger probes use the discrete-point probing method to record streams of points from the part surface. In discrete point probing, the CMM lifts the probe head from the surface of the workpiece, moves it forward and lowers it until contact is made again, this happens for every data point that is collected. This single point procedure is relatively slow and is unsuited for the efficient measurement of complex shaped workpieces and applications where large amounts of data are required, such as form evaluation. The availability of dual-purpose probes that are able to utilise continuous scanning and touch trigger operation allows fast set up procedures when switching modes.

Analogue probes for continuous scanning are designed to send an uninterrupted flow of data back to the system computer; they eliminate the auxiliary movements required by discrete (point-to-point) measuring probes. CMMs use two types of continuous scanning methods, Open Loop and Closed Loop, depending on whether the geometry of the workpiece is defined or undefined respectively

Open loop scanning

This method is a high-speed technique used for known or defined shapes and whose geometry has few curves and surfaces, allowing the probe to maintain contact with the surface.

The machine movement is controlled by the nominal geometric data held in the CMM part program. The magnitude of error between the actual surface and the nominal surface detail is recorded. Acquiring a large number of data points ensures repeatability for diameter and position and a much better definition of the surface form.

Closed loop scanning

This technique is useful for digitising undefined, convoluted shapes. The analogue-scanning probe detects changes in surface directions of the part and adjusts its position to maintain contact with the workpiece. Examples of parts suited to this method are turbine blades, gears, cams and rotors.

Continuous scanning probes

Analogue probes when used in scanning-mode remain in constant contact with the surface of the workpiece during the scanning cycle (figure 41). The machine control system ensures that by detecting deviations and rectifying them it maintains a consistent contact force.

True 3-D systems are isotropic - the same probing force is exerted in all three measuring axes simultaneously. These types of probe are suitable for the inspection of convoluted surface parts such as gears, cams, rotors and hobs, where the measurements are made with 3-D movements that require a precise determination of the surface points to define the workpiece’s true geometry. The probes are usually low mass and have high structural stiffness and friction free viscous damping which allows for improved dynamic performance characteristics.

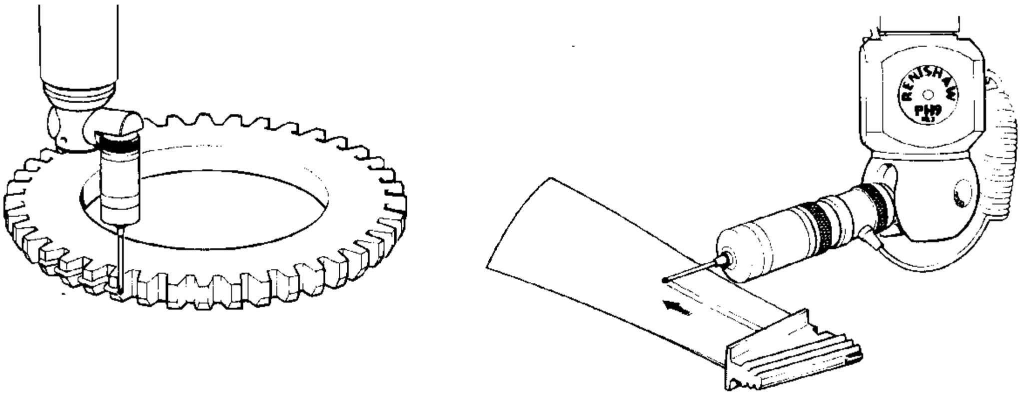


Figure 41 Examples of continuous scanning probes used for gear tooth and turbine blade measurement

2-D probing systems are not as accurate as they cannot use all three probe axes simultaneously. Probe size compensation takes place in a plane, not in space therefore they cannot retrieve the part surface vectors and perform true 3-D measurements. These probes have two operating modes, axial scanning (figure 42) and radial scanning (figure 43). In axial scanning, only the axial-probe is free to move, the other two axes are locked. This mode is suitable for profiling.

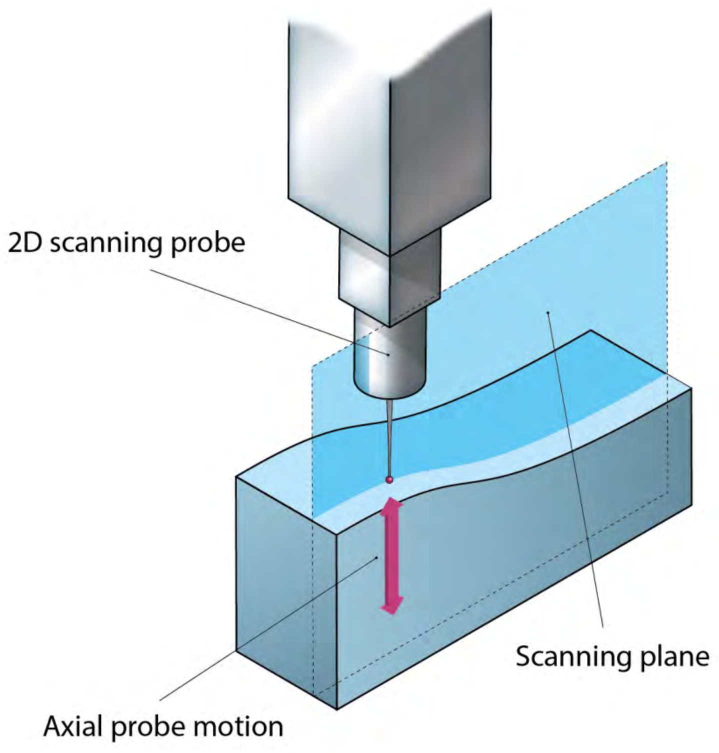


Figure 42 Operation of 2-D scanning head – axial probe motion

In radial-scanning mode (figure 43), the axial probe axis is locked and the other two are free to move. Radial scanning is used in contouring applications. 2-D probes are able to compensate for probe tip size in the scanning plane only; each measured point is affected by cosine error. This method is not suitable for the inspection of convoluted surface parts.

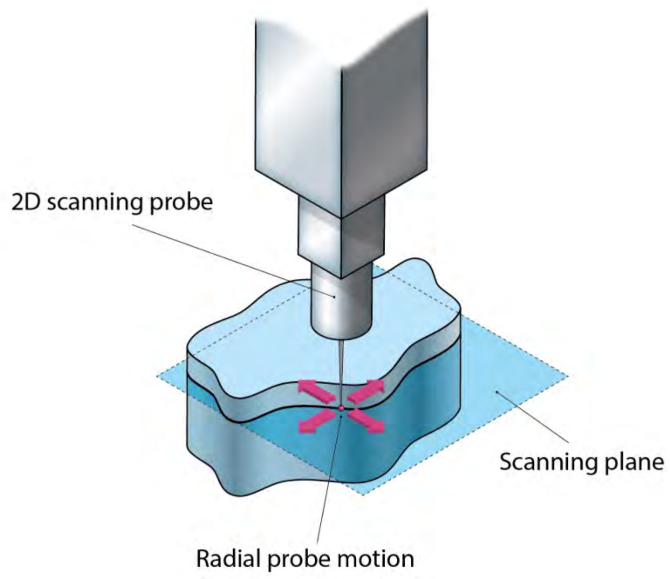


Figure 43 Operation of 2-D scanning head – radial probe motion

Five axis scanning

Five-axis scanning probes (figure 44) are designed to minimise the dynamic effects of CMM motion at very high measurement speeds.

Figure 44 A five-axis scanning probe (© Renishaw plc 2014)

Five-axis scanning allows the stylus to follow continuous paths around complex components without having to leave the surface to change stylus or index the head (figure 45).

Figure 45 A sweep scan round a curved surface (© Renishaw plc 2008)

Choice of scanning styli

The choice of styli will depend on the scanning application and the type of scanning probe used. The use of a stylus that has the same diameter as the finishing cutting tool used to produce the part is recommended.

The stylus should be as short as possible to prevent excessive bending, but long enough to prevent fouling of the shank.

Wherever possible ball ended styli should be used, however, if the workpiece has undercuts that are likely to trap the ball then a parallel-sided stylus should be selected.

The most commonly used styli in coordinate measuring machines are ruby spheres. If ruby comes in to contact with soft materials like aluminium alloy or pure titanium, some material from the workpiece will build up on the ruby surface (adhesive wear[3]). This effect will be intensified on frequent contact.

Choice of material is important and apart from the traditional ruby stylus silicon nitride, Zirconia and Diamond!Scan® tips are available. For instance, silicon nitride is not as hard as ruby but has a higher pressure resistance. This can have a positive effect on the stylus friction behaviour when scanning very hard or very soft materials. However, silicon nitride spheres can suffer from abrasive wear when scanning steel. Diamond!Scan is useful for scanning soft aluminium allows as there is less likely hood of material build up. The downside of Diamond!Scan styli is there initial cost and the limitation on available stylus tip dimensions.

When scanning cast iron in a heavy duty cycle, Zirconia is more resistant to 'abrasive wear'.

Wear and build-up on a stylus tip not only depends on sphere material, but also on workpiece material, surface finish, coating *etc*.

All stylus tips should be examined on a regular basis for signs of damage and material build up even if they are only ever used in a discrete point probing mode.

Chapter summary

- Be aware of the differences between discrete point and scanning.
- Understand open and close loop scanning.
- Be aware of the choices of stylus tip when making scanning measurements.

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[3] Adhesive wear can be found between surfaces during frictional contact and generally refers to unwanted displacement and attachment of wear debris and material compounds from one surface to another.

Non-contact probing systems

11

IN THIS CHAPTER

- Non-contact probing systems
- Points to be aware of with non-contact scanning systems
- National FreeForm Centre
- FreeForm reference standard

Non-contact probing systems are replacing the more traditional contact probing systems in applications where sped is required or where the material properties are not suitable for contact probing. These systems are fast and collect many data points. However, the user should be aware of the limitations of such systems. Currently traceability is difficult to demonstrate for such sensors and specification standards relating to performance verification are at the early stages of development.

Figure 46 A non-contact probing system

Non-contact probing systems

The trend in sensor development over the last decade has been directed toward non-contact optical sensors (figure 46 and figure 47). These sensors combine the elements of optics, video and laser technologies. They can gather up to 20,000 data points per second with extreme accuracy. Combined with powerful mathematical engines, rapid analysis of large amounts of dimensional data can be undertaken. This section gives an introduction to these sensors but does not aim to give best practice on their use.

An example of a non-contact probe is the laser probe. With this type of probe a precisely focused laser or infrared beam is directed towards a point on the workpiece. When the beam strikes the surface of the workpiece, it forms a spot image. The reflected light is then focussed on a photoelectric array. Any variation in the surface distance from the sensor results in a change of the position of the spot image on the array. The laser probe is capable of scanning at a higher speed than a touch trigger probe, however, the touch probe offers a higher resolution than the laser. The signal from the laser probe emulates that of a standard touch trigger probe. This ensures that it can be used with existing CMM software and requires no specialist programming techniques.

Because the laser probe causes no distortion of workpiece surfaces it is well suited for the inspection of pliable and delicate materials. Typical applications of such systems include the measurement of seating and dashboards in automobiles, plastic mouldings, clay models and rapid prototyping models. Laser probes can produce accurate measuring systems but it should be noted that errors could be produced for certain types of workpiece material due to their optical reflection properties.

Figure 47 Optical trigger probe system (© Renishaw plc 2006)

Some non-contact sensors incorporate a structured light source that emits a plane of light (Figure 46). When this plane intersects the part, a line of light forms along the contour of the workpiece. The line is detected by an image sensor, which transforms it into a measurable digital image from which it is possible to triangulate and calculate the (x, y, z) co-ordinates of hundreds of points along the line.

Non-contact sensors can scan faster than analogue sensors, but they may have limitations in accessibility to all workpiece features. Because of this frequent re-orientations of the head may be required during the scanning process resulting in a reduction of the effective overall system throughput.

Generally optical systems are not used for high accuracy applications and camera based optical systems are limited by the size and number of pixels and resolutions of the camera image (see Measurement good Practice Guide No.39 *Vision Systems*).

Non-contact scanning methods can be combined with analogue scanning to extend the application of CMMs to include inspection of small complex parts.

Most CMM manufacturers nowadays offer multisensor systems that include contact and non-contact measuring devices. The CMM can be programmed to recognise when a touch trigger probe is in use or when an optical system is operating. Autochange probe equipment or multiple function-probing heads facilitates switching between systems.

One of the key benefits of a multisensor system is the flexibility of operation it gives the user. Parts that require tactile and vision measurements can be inspected on the same machine and do not have to be transferred from the CMM to a separate vision system therefore facilitating economic inspection.

Figure 48 and figure 49 show other optical sensor configurations.

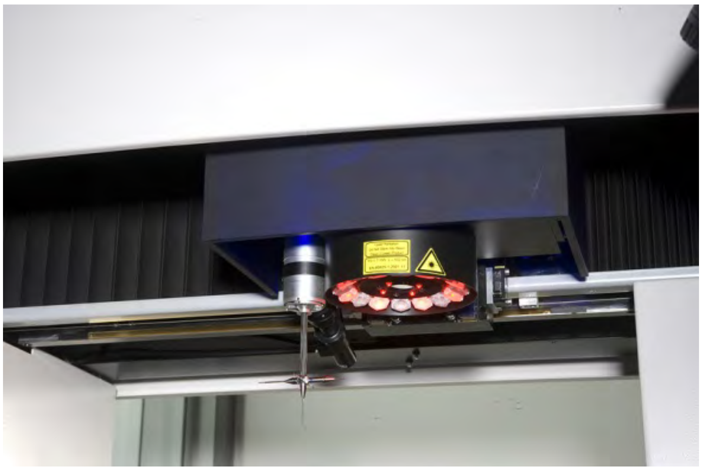


Figure 48 Combined probe head (© Zeiss)

Figure 49 An optical probe head (© Zeiss)

Points to be aware of with non-contact scanning systems

Non-contact optical probes are sensitive to the optical properties of the surface being measured. Factors that can affect performance include colour, reflectivity and surface texture. The data from the systems can also contain many rogue points due to stray reflections and some filtering of the data is necessary. However, care must be taken that any removed points are from genuine stray reflections and not from surface defects. Often measurements have to be made with some kind of dulling agent applied to the surface.

National FreeForm Centre

The National FreeForm Centre based at NPL is available to help you make best use of non-contact probing technologies.

Support available includes:
- information on current NPL Freeform Standards for verifying scanning systems;
- opportunity to attend meetings of practitioners and users focused on common issues;
- trial facilities for different technologies including CMMs with tactile and non-contact probes, laser scanners, articulated arms, fringe projection systems, and point cloud processing software;and
- access to independent consultancy providing evaluation of different techniques.

FreeForm reference standard

To aid in the verification of non-contact dimensional freeform co-ordinate measuring systems, such as those employing laser scanning and fringe projection technologies the FreeForm reference standard (Figure 50) has been designed and developed by the National FreeForm Centre at the National Physical Laboratory (NPL).

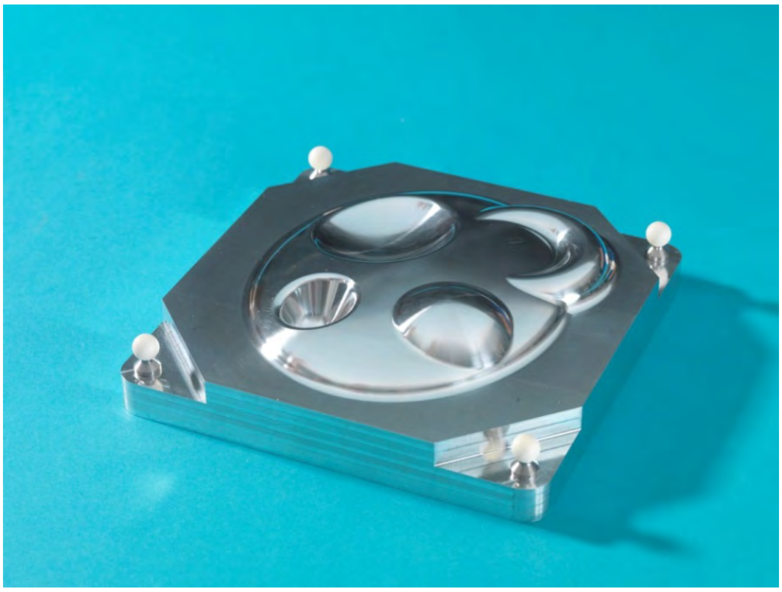


Figure 50 NPL high precision traceable FreeForm reference standard, the standard is available in a number of sizes.

The reference standard can also be used to verify the performance of Cartesian CMMs fitted with tactile probing systems.

The standard bears several geometrical forms that are blended to form a single surface that tests various aspects of instrument performance. Ceramic tooling balls or hemispheres on each corner of the standard aid registration. Supplied with each standard is a calibration certificate, the relevant CAD model and traceable measurement data files.

It is good practice to use a standard such as this, or something similar representing typical day-to-day measuring tasks to verify the performance on non-contact scanning systems. Such an item allows day-to-day checks to be carried out and also allow the evaluation of new measurement technologies.

Chapter summary

- Be aware of the different types of non-contact probing system.
- Be aware of the issues that can affect non-contact systems such as colour, reflectivity and surface texture.
- Be aware of the national freeform centre.
- Make use of reference standards.

Published Standards

12

IN THIS CHAPTER

This measurement good practice guide has provided an overview of the various considerations relating to CMM probing. The reader is advised to keep up-to-date with the standardisation work in this area. This chapter lists the currently available CMM specification standards and gives an overview of the work in progress. Knowledge of the standards will allow the reader to more fully understand manufacturers' specifications and the processes involved in the performance verification of probing systems.

Published standards

International Standard ISO 10360 covers CMMs. This standard has nine parts:

- 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*
- ISO 10360-3: 2000 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 3: CMMs with the axis of a rotary table as the fourth axis*
- ISO 10360-4: 2000 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 4: CMMs used is scanning measuring mode*
- ISO 10360-5:2010 Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 5: CMMs using single and multiple stylus contacting probing systems
- ISO 10360-6:2001 Geometrical Product Specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 6: Estimation of errors in computing Gaussian associated features
- ISO 10360-7:2011 Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 7: CMMs equipped with imaging probing systems
- ISO 10360-8:2013 Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring systems (CMS) — Part 8: CMMs with optical distance sensors
- ISO 10360-9:2013 Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring systems (CMS) — Part 9: CMMs with multiple probing systems

ISO 10360-1 is relevant to this guide as it defines the terminology relating to the probing system and the stylus system. It also has a section on scanning terms.

Part of ISO 10360-5 describes how to verify the performance of the probe for both single and multiple stylus contacting probing systems. ISO 10360-4 extends this test for scanning systems.

Since the last revision of this guide part 2 and part 5 have been updated and new parts 6, 7, 8 and 9 have been published. The single stylus probing test that appeared in ISO 10360-2: 2001 does not appear in the current edition of ISO 10360-2. The test is now in the new edition of ISO 10360-5. Parts 8 and 9 are relevant to those systems fitted with optical probing systems.

To keep up-to-date on the latest revisions visit the catalogue on the ISO website www.iso.org.

The following parts of the standard are currently under development as of August 2014. Both have sections on evaluating probings made with each of these technologies.

ISO/DIS 10360-10.2 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring systems (CMS) – part 10: Laser trackers for measuring point-to-point distances*.

ISO/DIS 10360-12 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring systems (CMS) – Part 12: Articulated-arm coordinate measurement machines (CMM)*

Summary

13

IN THIS CHAPTER

- Summary of this guide

This measurement good practice guide has provided an overview of the various considerations relating to CMM probing. The pertinent points of this guide are summarised below.

Summary of this guide

Many points of best practice have been highlighted in this guide. The main points of best practice relating to CMM probes can be summarised as follows:

- Understand the basic designs of touch trigger probes.
- Understand pre-travel variation.
- Be aware of the types of articulating probe head, both manually articulating and motorised.
- Be aware of good practice when using probe head extension bars.
- Choose the most appropriate probe for the job.
- Use a suitable probing force – check with gram gauge.
- Use the most appropriate approach velocity.
- Keep the stylus tip and calibration sphere clean.
- Check that the stylus stem does not contact the workpiece.
- Choose the most appropriate stylus combination for the job and keep it as stiff as possible.
- Clean stylus and calibration sphere and check that it is adequately clamped.
- Check correct calibration sphere diameter is entered into the software (check against latest calibration certificate).
- Qualify styli using a probing strategy that matches the probing directions on the workpiece. At the very minimum, probe two points close to the pole and four points on the equator. Use automatic calibration routines if available. Qualify the stylus frequently.
- Check that sensible values have been recorded - keep all printouts.
- keep records and check against any history.
- Measure a known artefact before measuring the workpiece.
- Be aware of the thermal implications when assembling stylus configurations.
- Be aware of how to choose the most appropriate stylus.
  Be aware of the effect of measurement strategy with regards to direction of approach and measuring speed on the results.
- Be aware of the differences between discrete point and scanning.
- Understand open and close loop scanning.
- Be aware of the choices of stylus tip when making scanning measurements.
- Be aware of the different types of non-contact probing system.
- Be aware of the issues that can affect non-contact systems such as colour, reflectivity and surface texture.
- Be aware of the national freeform centre.
- Make use of reference standards.
- Keep everything clean.
- Look for the unusual - question every result (not just the ones you do not like!).
- Be aware of the relevant CMM standard specifications.

Glossary of terms

14

IN THIS CHAPTER

- 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.

This glossary of terms is taken from the Renishaw technical manual except where stated

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.
Articulating probing system	A probing system which can be orientated in various spatial angular positions by means of a manual or motorized positioning device (ISO 10360).
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.
Contact probing system	Probing system which needs material contact with a surface being measured in order to function (ISO 10360).
Discrete point probing	A particular probing mode where the recording of an indicated measured point is assessed directly after an intermediate point has been left. (ISO 10360)
E-bar or ebar	An abbreviated name for extension bar.
Edge triggering	The ability of a non-contact probe to automatically locate the edge or boundary of contrasting features on the workpiece.
Extension	Device for increasing the reach of a probe or stylus. Extensions placed between the probe and the probe head are known as 'extension bars' or 'E-bars'.
Indexing head	An articulating probe head that may be oriented and locked in a number of kinematically seated spatial positions. After the stylus tips have been qualified at each required position, the head may be moved to any of these positions without requalification.
Jog	An incremental move of an indexing head to an adjacent position.

Kinematic Seating	A mechanism in which the spatial position of a movable component, when located in the seated position, is kinematically constrained by 6 contact points formed by a system of rollers (or 'V' grooves) and ball bearings.
Kinematic switching probe	A contact probe in which the kinematic seating forms an electrical circuit that is broken by the action of displacing the stylus, to provide the trigger signal.
Kinematics	The science of motion, independent of force.
Lobing characteristics	Used to describe the form measurement error of kinematic switching probes resulting from the tri-lobed pretravel pattern (in the X-Y plane) that characterises this type of sensor mechanism. Refer to pretravel variation.
Non-contact Probe	Probing system which needs no material contact with a surface being measured in order to function. (ISO 10360).
Optical Triangulation	A non-contact method in which the position of a focused laser spot is reflected from the target onto an optoelectronic sensing device to determine the distance of the target.
Optical trigger Probe	An optical non-contact probe that provides a trigger signal when the target is at a pre-set distance.
Overtravel	The distance that the CMM takes to stop following the assertion of a probe trigger signal.
Overtravel force	The force applied by the stylus ball to the surface at a defined overtravel displacement.
Pretravel	The displacement from the point where the stylus ball contacts the workpiece, to the point where a probe trigger is asserted.
Pretravel variation	Also called form measurement error or lobing, this source of systematic error is predominant in kinematic switching probes where a tri-lobed pretravel pattern (in the X-Y plane) characterises this type of sensor mechanism.
Probe	The device that generates the signal(s) during probing. (ISO 10360).
Probe head	A device fitted to the quill 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.
Probe qualification	The establishment of the parameters of a probing system necessary for subsequent measurements (ISO 10360).
Ram	The component of a CMM that carries a probing system. Also called the quill. (ISO 10360).
Reference sphere	Spherical material standard of size placed within a measuring volume of a CMM for the purpose of probing system qualification.
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	A particular probing mode for taking consecutive measured points in order to characterise lines on an inspected surface.
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.
Servo positioning head	A motorised articulating probe head that may be oriented to virtually any desired spatial position with fine resolution. The position is held during probing by the servo control system. High precision rotary position encoders eliminate the need for requalification.
Shank	A plain or tapered shaft for mounting a probe or probe head to the quill of the CMM.
Stylus	Mechanical device consisting of a stylus tip and a shaft. (ISO 10360).
Stylus tip	The physical element that establishes the contact with the workpiece. (ISO 10360).

Stylus changing	A system based on a highly repeatable kinematically constrained coupling, to allow the fast exchange of stylus configurations without requalification.
Touch trigger probe	A discrete point taking type of contact probe.
Trigger force	The force that must be applied at the stylus tip to trigger the probe.
Unidirectional repeatability	The variation of the position of successive triggers taken in the same direction of triggering under constant conditions.

For a full list of terms see ISO 10360-1:2000 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM)—Part 1: Vocabulary*

Health and safety

15

IN THIS CHAPTER

- Mechanical
- Hazards associated with laser illumination
- Chemical

When making measurements on 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

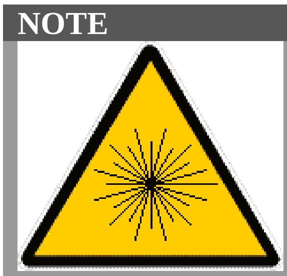
Many of the items you are measuring may be relatively heavy. The appropriate lifting techniques and equipment should always be used and safety shoes worn. Operators should wear laboratory coats or overalls for safety reasons and to prevent fibres shed from clothing from falling on items being measured.

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

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IN THIS CHAPTER

- Appendix A Links to other useful sources of information.
- Appendix B Further reading.
- Appendix C Manufacturers

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

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.

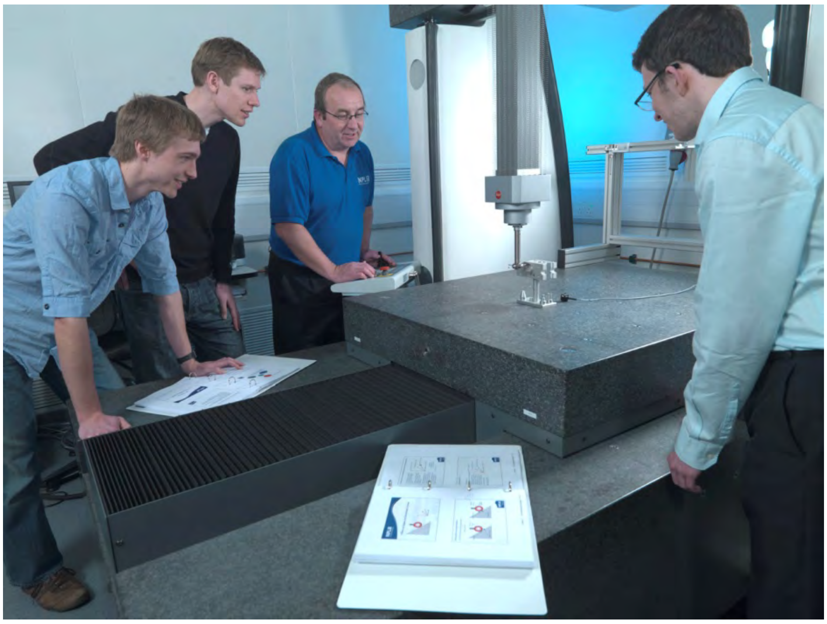
Accreditation by UKAS demonstrates the competence, impartiality and performance capability of these evaluators.

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 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

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

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.

Coordinate Measuring Machines and Systems edited by Robert J. Hocken and Paulo H, Pereira CRC Press Second Edition 2011 ISBN 978-1-57444-652-4.

Precision Engineering 19:85, 1996 *Error compensation for CMM touch trigger probes* W. Tyler Estler, S. D. Phillips, B. Borchardt, T. Hopp, C. Witzgall, M. Levenson, K. Eberhardt, M. McClain, Y.Shen and X. Zhang.

Fundamentals of Dimensional Metrology, Third Edition, Ted Busch, Roger Harlow, Richard L. Thompson.

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

BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML. *Guide to the Expression of Uncertainty in Measurement*, International Organization for Standardization, Geneva, Switzerland.

Improve the Performance of Touch-Trigger Probes, April 1999 Steve Philips and Tyler Estler (www.qualitymag.com).

NIST Model Boosts CMM Accuracy, April 1998 Melissa Larson (www.qualitymag.com).

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

Other useful information is published regularly in journals such as Quality Today, Measurement Science and Technology, Metrologia, Measurement and Precision Engineering.

Appendix C Manufacturers

The following is a list of probe and stylus manufacturers and distributors. This is by no means a full list and the appearance of a manufacturer in this list is not an endorsement of its products.

Renishaw are both a manufacturer of probe heads and a supplier of styli and accessories for CMM probes. They can be contacted at New Mills, Wotton-under-Edge, Gloucestershire, GL12 8JR. Renishaw can also be found at www.renishaw.com. This site contains various documents that can be downloaded. .

Heidenhain are a German manufacturer of touch trigger probes (www.hiedenhain.com).

Fred V. Fowler Co Inc is an American manufacturer of touch trigger probes. They can be contacted at 66 Rowe Street P.O. Box 299 Newton, Ma 02466 or at www.fvfowler.com.

SWIP U.K, a division of Oakwade, is a supplier of CMM styli and accessories. They can be contacted at Unit 21, Hartlepool Workshops, Usworth Road Industrial Estate, Hartlepool, TS25 1PD. SWIP can be found on the web at www.saphirwerk.com

N J Metrology PO Box 413, Bedford, MK41 9ZP can also supply SWIP and Renishaw products – contact website: www.njmetrology.com.

Tesa UK, Halesfield 13, Telford, Shropshire, TF7 4PL is a manufacturer of CMM probes (www.tesagroup.co.uk).

Werth Messtechnik. Manufacturers of fibre probes.