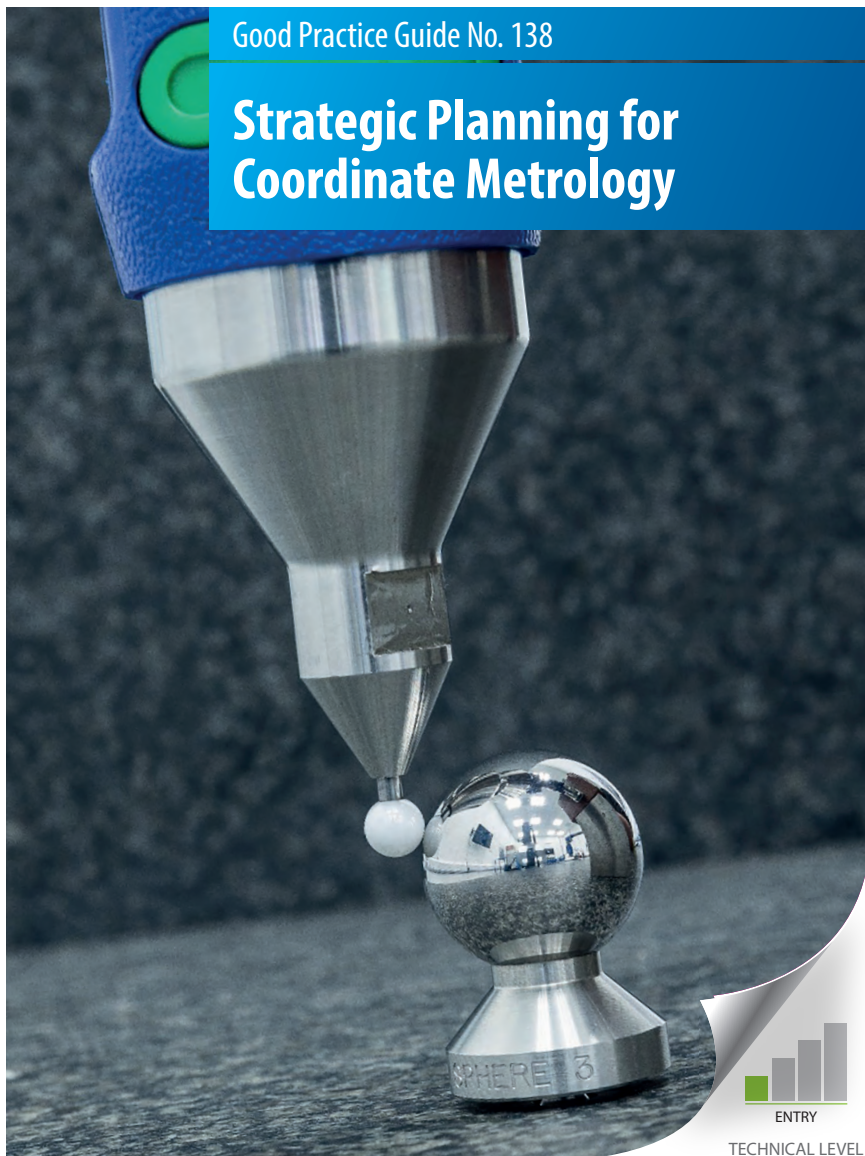


Good Practice Guide No. 138

Strategic Planning for Coordinate Metrology



ENTRY

TECHNICAL LEVEL



Department
for Business
Innovation & Skills

FUNDED BY BIS

Good Practice Guide No. 138

Version 1.0

Published in the United Kingdom 2016

© NPL Management Limited, 2016

ISSN

1368–6550

NPL Authors

Nikita Marwaha

Keith Bevan

CMS Contributors

Randell L Gruver

Matthew Ilardo

Rina Molari Korgel

Robert Mclvor

National Physical Laboratory

Hampton Road

Teddington

Middlesex

TW11 0LW

Good Practice Guide enquiries: **020 8943 6356**

E-mail: **gpg@npl.co.uk**

www.npl.co.uk/contact

Find out more about NPL measurement training at **www.npl.co.uk/training**
or our new online study programme at **www.npl.co.uk/e-learning**

Front cover image: *A hard-probe used on an articulated arm measuring instrument (Source: NPL).*

Guide Information

What is it about?

This document was designed for anyone who requires to strategically plan for coordinate metrology. Written in collaboration with the Coordinate Metrology Society, the information provided in this Guide is intended to complement the Coordinate Metrology Society Conference (CMSC).

Who is it for?

This guide is for users who want to gain familiarity with the fundamental principles of coordinate metrology in the context of dimensional measurement. It is designed for anyone who requires to strategically plan for coordinate metrology.

What is its purpose?

The purpose of the guide is to provide underpinning metrological knowledge, focusing on coordinate metrology in particular, in order to promote good practice when using portable coordinate measuring systems.

What is the prerequisite knowledge?

This guide is at entry/intermediate level and it does not assume any specific background knowledge.



The National Physical Laboratory (NPL)

- 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.
- NPL's mission is to provide the measurement capability that underpins the UK's prosperity and quality of life.



Primary Contributor

Coordinate Metrology Society

Founded in 1984, the Coordinate Metrology Society (CMS) is a large membership of users, service providers, and original equipment manufacturers of close tolerance, industrial coordinate measurement technology. These metrology systems include, but are not limited to, inspection software, traditional Coordinate Measuring Machines (CMMs), theodolites, Global Positioning System (GPS), laser projection systems, laser trackers, laser radar, photogrammetry/videogrammetry systems, scanning devices, and articulating arms.

The CMS is devoted to expanding and promoting the usage and education of metrology and their mobile metrology systems. The membership assembles each year at the Coordinate Metrology Society Conference (CMSC) to learn about the latest in-use advancements and new product developments in measurement software or systems that produce, utilise and analyse three-dimensional coordinate data. Users from all relative industries also share their experiences and expertise through presentations during the conference.

The CMS also publishes ***The Journal of the CMSC*** twice a year and devotes its pages to the finest white papers presented by industry experts each year at the conference. Topics covered include diverse applications of portable, three-dimensional measurement technology for documentation purposes or as the crux for manufacturing and assembly. The society also published ***CMSC WORLD***, a quarterly eNewsletter that delivers the latest news, case stories, feature articles, and more covering the field of metrology.

The CMS determined a clear need for a certification programme based on an ageing workforce, new skill requirements from industry, and the ever-increasing need for metrology expertise. Today, CMS certification credentials aid in quantifying a potential employee or service provider's knowledge of metrology, which is essential to ISO certified manufacturers and companies with Quality Management Systems.

Via the harmonious missions of education combined with the previously mentioned certification endeavour, CMS, its membership, and NPL are strategic partners in developing materials for the edification of our focused 3D metrology community.

For more information on CMS, please visit the website listed below:

The Coordinate Metrology Society

2537 Elk Hollow Lane
Weatherford, TX
76085, USA

Telephone: +1 425 802 5720
Email: treasurer@cmssc.org
www.cmssc.org

Contents

Foreword	08
-----------------	----

Introduction	11
---------------------	----

Chapter I

Introduction to Measurement	15
------------------------------------	----

The fundamental concepts of metrology	16
---------------------------------------	----

The importance of measurement	17
-------------------------------	----

Traceability	18
--------------	----

Measurement units	19
-------------------	----

Chapter II

Design Document Requirements	21
-------------------------------------	----

Design documents	22
------------------	----

Blueprints and Technical Drawings	23
-----------------------------------	----

Chapter III

Measurement Device Knowledge	25
-------------------------------------	----

Metrology concepts underpinning device knowledge	26
--	----

Environmental Conditions	26
--------------------------	----

Measurement Uncertainty	26
-------------------------	----

Where does uncertainty come from?	27
-----------------------------------	----

What is an uncertainty budget?	28
--------------------------------	----

Why is measurement uncertainty so important?	28
--	----

Accuracy and Precision	28
------------------------	----

Measurement device knowledge	30
------------------------------	----

Evaluate size/volume requirements	30
-----------------------------------	----

Identify appropriate accessories	30
----------------------------------	----

Identify ergonomic issues	30
---------------------------	----

Evaluate material constraints	30
-------------------------------	----

Evaluate time constraints	30
---------------------------	----

Evaluate accessibility	31
------------------------	----

Types of common metrology equipment	32
-------------------------------------	----

Chapter IV

Pre-measurement Planning	37
---------------------------------	----

Metrology concepts underpinning pre-measurement planning	38
--	----

Measurement Strategy	38
----------------------	----

What happens without a measurement strategy?	38
--	----

Environmental Influences	40
--------------------------	----

Vibration	40
-----------	----

Draughts	41
----------	----

Temperature	41
-------------	----

Pre-measurement planning	42
--------------------------	----

Determine uncertainty budget	42
------------------------------	----

Optimise equipment stations	44
-----------------------------	----

Determine data collection	44
---------------------------	----

Plan reference system	44
-----------------------	----

Determine order of measurement	44
--------------------------------	----

Estimate data collection time	44
-------------------------------	----

Determine naming conventions	45
------------------------------	----

Identify safety requirements	45
------------------------------	----

Plan coordinate systems	45
-------------------------	----

Plan traceability and documentation	45
-------------------------------------	----

Create a documentation plan	47
-----------------------------	----

Plan subject temperature compensation strategy	47
--	----

Maintain equipment	47
--------------------	----

Chapter V

Performing Measurement Operations	49
--	----

Verification of calibration status	50
------------------------------------	----

Setup equipment	50
-----------------	----

Perform <i>in-situ</i> (field) check	51
--------------------------------------	----

Install reference features	51
----------------------------	----

Measure reference features to create a coordinate system	51
--	----

Mitigate environmental influence	51
----------------------------------	----

Measure features of interest	52
------------------------------	----

Re-check reference features	52
-----------------------------	----

Perform device move if required	52
---------------------------------	----

Perform quality assurance of data set	52
---------------------------------------	----

Establish traceability	53
------------------------	----

Chapter VI

Analysing Data 55

Compare measurement data
to design specifications 56

 Evaluate GD&T 56

Combine and evaluate alignment 56

Register data sets to reference system 57

Optimise data 57

Construct geometry 57

Calculate uncertainty and its impact 57

Statistical techniques and calculations 58

Chapter VII

Conclusion 59

Chapter VIII

**References &
further reading** 61

References 62

Further reading 63

Contact NPL 65

Foreword

Personnel certification is at its core, a means by which skill and knowledge demonstration to a performance standard is documented. Not to be confused with a certificate of completion, certification credentials are bestowed upon an individual or entity by a certifying agency. Initial awarding of certification is the beginning of a professional journey. The journey should be rich and fulfilling, challenging the certified professional with continuing education, and a commitment to growth within their discipline as well as demonstrating adherence to a code of ethics. Certification is both a professional and personal achievement that communicates skill, knowledge, and character as defined by the certifying agency.

The Coordinate Metrology Society (CMS) is such an agency. The CMS is the preeminent organisation dedicated to promoting portable 3D technology. The annual conference, is best described as a unique combination of trade show, expert technical presentations and networking opportunities. The proliferation of close-tolerance, relatively large volume portable 3D measurement devices, and software has benefited many sectors of manufacturing and inspection. Calibrated and certified measurement equipment is demanded, but what about the operator? The sophisticated capabilities of these products, and the variation that can be introduced by an operator, begs the question of operator competence. Aerospace, Nuclear, and Service provider representatives have raised the issue of personnel certification to the Coordinate Metrology Society, and they responded! Our investigation began with an analysis of the 'need'. Analysis results included:

- A portable 3D metrology certification does not currently exist.
- A properly structured certification program would be of definite value.
- Currently equipment must be calibrated; however, the operator, the greatest potential source of error, is not required to be certified.
- Certification should be multi-level (Level 1 knowledge, Level 2 skill) to delineate degree of capability and responsibility.
- Certification should indicate mastery of a core body of knowledge with additional certifications for equipment/software.
- Hardware/software certification should demonstrate appropriate technical knowledge as well as proficiency.
- There should be certified examiners for each hardware group.
- There may be areas where certification would be application specific.
- Eighty percent of respondents learned their skills through on-the-job informal training.

- Thirty-five percent of professionals using these technologies have 20+ years of experience.
- Sixty percent of the survey respondents recommended a partnership with a compatible organisation experienced in administering personnel certification.

This guide is intended to provide an outline documenting the knowledge necessary to successfully achieve an understanding of the steps required when strategically planning for coordinate metrology. The areas discussed include design documents, device knowledge, pre-measurement planning and data analysis. Targeted towards the 3D metrology community, this guide aims to improve the understanding and awareness of measurement good practice.



Mr Randell L Gruver
CMS Certification Chair
Boeing Employee Development

Introduction

This guide aims to highlight the importance of and provide guidelines for implementing strategic planning and good practice in *coordinate metrology*.

Coordinate metrology is a branch of dimensional measurement that involves measuring geometric features and freeform shapes using the principles of coordinate measurement and an array of 3D technologies.

Its role in the engineering and manufacturing industry is often to assess a manufactured object against a design specification. Therefore, the measurement professionals involved in the measurement process need to have an understanding of the design and documentation process. Likewise, designers need an understanding of *metrology* - the science of measurement - in order to design an object that can be easily measured.

To emphasise the links between design, manufacturing and measurement, this document is structured as follows:

- **Chapter 1** will give an introduction to the fundamental principles of measurement
- **Chapter 2** will look at interpreting design documents
- **Chapter 3** will discuss measurement device knowledge, using the measurement principles introduced in Chapter 1 to identify a measurement strategy
- **Chapter 4** will provide guidance on pre-measurement planning and the methods used to ensure that the measurement strategy is evaluated against environmental factors
- **Chapter 5** will look at performing coordinate measurement operations using the concepts already discussed.
- **Chapter 6** will address the final stage of carrying out a measurement – analysing data and the ethics involved in responding to the data collected.

Using this structure has the added benefit of defining the five key good practice duty areas to follow, as defined by CMS. These are:

- 1) Design document requirements
- 2) Measurement device knowledge
- 3) Pre-measurement planning
- 4) Performing measurement operations
- 5) Analysing data

Such practical guidelines ensure that scientific principles of measurement are applied. Similarly, NPL has its own six guiding principles of measurement. These are:

- 1) Make the right measurement
- 2) Use the right measurement tools
- 3) Use the right measurement procedures
- 4) Employ the right people to do the measurement
- 5) Review your measurement regularly
- 6) Demonstrate how consistent the measurement is

Both CMS's duty areas and NPL's guidelines communicate similar concepts. However, for the purpose of this guide, we will be following the outline provided by the CMS duty areas, complementing the CMSC.

In summary, this document highlights the best practices used to perform measurements in an accurate, reproducible and reliable way.

Chapter I

Introduction to Measurement

- The fundamental concepts of metrology
- Traceability
- Measurement units

The overarching goal of this Guide is to ensure that better measurements are made. In order to do this, in this chapter we need to briefly examine the basic principles of measurement. Once we have addressed the core concepts of metrology, we will then bring our attention towards applying them to the coordinate measurement requirements in Chapters 2 to 6. So, first, let's define measurement.

The fundamental concepts of metrology

Measurement is: **'the process of experimentally obtaining one or more quantity values that can be reasonably attributed to a quantity'** ¹.

From telling the time and checking the speed of your car, to monitoring pollution and studying biomolecules — measurement is vital to industry and everyday life. *Coordinate measurement* is a branch of dimensional measurement that is concerned with measuring the sizes and dimensions of an object using coordinate geometry. Applications of coordinate measurement include measuring the size of a room using a laser tracker (we will look at coordinate measurement instruments in Chapter 3), as well as various other uses in the automotive and aerospace industries.

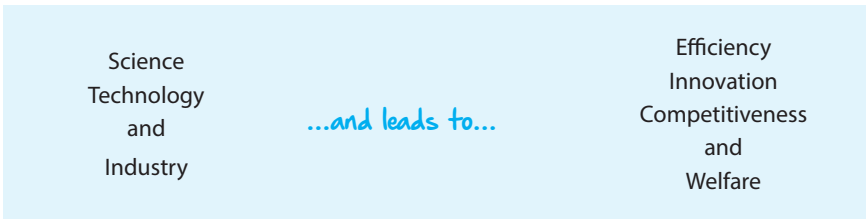
Precise measurements of items ensure that they work correctly and significantly reduces the likelihood of failure. This is where *metrology* comes in.

The word 'metrology' has its roots in the Greek word 'metron' ('μετρον' – to measure). Nowadays, it is recognised as the science of measurement and its application. This includes the theoretical and practical aspects of measurement.

Metrology activities:

- **Define** internationally accepted units of measurement
- **Realise** the units of measurement (by scientific methods)
- **Establish** *traceability chains* (determining and documenting the value and accuracy of a measurement)

Within these activities, metrology underpins:



Metrology falls within three distinct categories:

- **Scientific metrology** – which defines and organises measurement standards
- **Industrial metrology** – which ensures adequate functioning of measurement instruments in the industry
- **Legal metrology** – which verifies and ensures the application of measuring standards

The importance of measurement

Measurement tells us about a property of something, enabling quantitative comparison. When carrying out dimensional measurements, this quantitative comparison is often against design specifications.

Before we discuss the design requirements of an object, it is important to understand the role of metrology and its impact in society. It influences, drives and underpins much of what we do and experience in our everyday lives, though it is often unseen. In coordinate metrology, the science of measurement underpins technological innovation such as robotic automation in manufacturing processes within the production line, economic activity by reducing the amount of waste produced in these processes and social impact with the development of scanners in the police force which help to analyse crime scenes following a traffic collision.



Figure 1: Measurement plays a role in much of our everyday lives, from buying petrol, to eating safe foods, it ensures the welfare of modern society.

Successful measurement depends on many requirements, including the following:

- **Accurate** instruments
- An understanding of **uncertainty**
- **Traceability** to national standards

The fundamental metrology concepts of accuracy and uncertainty are explored more in Chapter 3. Next, we will take a look at the concept of traceability.

Traceability

Let's look at the concept of traceability by addressing an important question:

How can we be confident that the measurements that we make are accurate representations of the thing that we are trying to measure?

In practice, this confidence is provided by ensuring that the measurements we make are traceable to the International System of Units, or SI units (Système International d'Unités). Formally agreed by the 11th General Conference on Weights and Measures in 1960, the SI is a globally agreed system of units, with seven fundamental base units from which all other units are derived. We will take a look at the units used in dimensional measurement next, but first let's return to traceability.

In principle, this *traceability* could be achieved by calibrating all measurement instruments against primary standards (realisations of the SI units plus a number of derived units) held at National Measurement Institutes (NMIs). However, in reality, it would be both impractical and costly to use primary standards alone to calibrate the huge number of instruments in use.

Hence, we typically establish traceability using an unbroken chain of calibrations which leads back to its origins in primary standards. We call this a '*traceability chain*'.

National Metrology Institutes have the important task to create the foundation for traceable measurements, namely by calibrating the reference standards of calibration laboratories and industry. These reference standards, when properly calibrated, may be distributed extensively, greatly improving ease of access and reduction in costs.

We will learn more about calibration and the importance of calibrating instruments in Chapter 3.

For now, it is important to understand that such terms alone do not lead to successful measurements. In order to obtain accurate, traceable measurements with low uncertainty, you must apply good measurement practice.

This can be done by:

- Employing trained staff
- Identifying possible sources of error (e.g.: environmental factors, inferior measuring equipment and poor measuring techniques)

Let’s take a look at the units used when recording a measurement and how the type of measurement – in this case dimensional measurement – affects the units being used.

Measurement units

When performing a measurement, the value found for a specific quantity must always be specified with a *unit*. Engineering design drawings and Computer Aided Design (CAD) models are expressed in different units around the world. The metric and inch systems are different sets of units of length, used in different regions of the world.

As previously mentioned, the SI units are comprised of seven units of measurement. The two base units most applicable to dimensional measurement are:

- The metre (m) – SI unit of measurement of length
- The kelvin (K) – SI unit of measurement of thermodynamic temperature

These two units are most applicable because length is directly influenced by temperature. Other base units with relevance to dimensional measurement include the unit of measurement of mass, the kilogram (kg), and the unit of measurement of time, the second (s).

The metre and the millimetre				
1 m	=	1000 mm	=	10^3 mm
1 mm	=	0.001 m	=	10^{-3} m

Table 1: On technical drawings it is common to express dimensions in millimetres.

Subdivisions of the millimetre				
100 μ m	=	0.1 mm	=	0.0 001 m (10^{-4} m)
10 μ m	=	0.01 mm	=	0.00 001 m (10^{-5} m)
1 μ m	=	0.001 mm	=	0.000 001 m (10^{-6} m)
1 nm	=	0.001 μ m	=	0.000 000 001 m (10^{-9} m)

Table 2: Subdivisions of the millimetre.

Inches and millimetres		
1 inch	=	25.4 mm
0.1 inch	=	2.54 mm
0.01 inch	=	0.254 mm
0.001 inch	=	0.0254 mm

Table 3: Relating the inch to the millimetre.

We have explored units of length, however, in dimensional metrology, you may also have to measure angles.

The measurement of angles has its own set of units. For practical angular measurements in engineering, the sexagesimal system of units is used almost exclusively where the angles are expressed in the terms a circle divided into degrees, minutes and seconds.

Unit conversion is crucial in measurements. Simple errors in converting units can lead to bad outcomes and serious economic damage.

Following this introduction to some of the fundamental metrological concepts used in coordinate metrology, we will look at the first of the five key duty areas in the next chapter, starting with design document requirements.

Chapter II

Design Document Requirements

- Design documents

Now that we have had an introduction to measurement and the ways in which it impacts our everyday lives, we will move onto the design documents used before measurement is even carried out. Interpreting these and learning to identify things such as tolerance is key to good practice in dimensional measurement.

Design documents

Design documents are used by the designer to outline the specifications, such as size, shapes, surface finish, that an object must meet once manufactured.

The production and acceptance of a finished workpiece can be thought of as the four following steps (see Figure 2):

- In the **design stage** of measurement, design documents are used by the designer to imagine the product as an ideal, perfectly manufactured object. All parts are assumed to be of perfect form and size.
- However, as the **manufacturing processes** turn this idealised concept into a real object, variations are inherently produced, causing the product to deviate from the idealised form.
- Then, during the **inspection stage** (we will cover this more in Chapter 5), the measurement specialist performs measurements to 'extract' a theoretical model of the real product.
- The **comparison stage** looks at the substitute element against the ideal form – comparing the final product against the design requirements. As a result, the product can be assessed against the original design document.

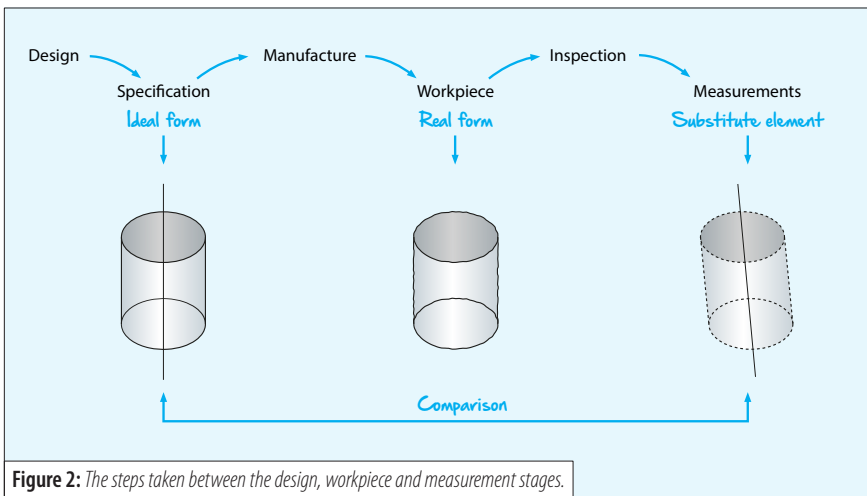


Figure 2: The steps taken between the design, workpiece and measurement stages.

Blueprints and Technical Drawings

Blueprints and technical drawings or Computer Aided Designs are the documentation from which measurement specialist can make observations on whether the manufactured object is 'sufficiently close' to the desired form. In order to know whether to accept or reject a manufactured part (in other words, whether it really is 'sufficiently close' to the desired form) it is essential to have:

- A specified *tolerance*
- The capability to measure the variation from the ideal dimensions

The International Organization for Standardization (or ISO) defines tolerance as the '*difference between upper and lower tolerance limits*,' with tolerance limits in turn being defined as '*specified values of the characteristic giving upper and/or lower bounds of the permissible value*.'

The American Society of Mechanical Engineers (ASME) defines tolerance as '*the total amount a specific dimension is permitted to vary*.'

When the 'amount' in question is a size, or length, then it is called a '*dimensional tolerance*.' Although necessary, dimensional tolerances are often not sufficient for unambiguous specification of a design.

As well as dimensional tolerances, a design document should contain geometrical tolerances, which provide constraints on the form, location and orientation of parts.

A good specification will then:

- Specify the sizes, geometry and tolerances necessary for proper functionality
- Provide sufficient information to allow a product to be manufactured and inspected
- Specify other necessary criteria such as requirements of appearance, storage, maintenance, etc.

In addition, for a specification to prevent ambiguity in design specifications, it needs to specify geometrical requirements too. These are particularly helpful when taking dimensional measurements. Geometries should have tolerances within which the real part is required to fit; these are *geometrical tolerances*. The use of dimensional and geometrical tolerances in combination is often known as '*Geometric Dimensioning and Tolerancing*' (GD&T).

Measurement Device Knowledge

- Metrology concepts underpinning device knowledge
- Measurement device knowledge

Metrology concepts underpinning device knowledge

In the previous chapter, we mentioned how successful measurements depend upon accuracy. In this chapter, we will see how this accuracy can be achieved by good knowledge of your measurement device. To understand this, we need to understand some common concepts of metrology including:

- Environmental conditions
- Measurement uncertainty
- Accuracy and precision

Environmental Conditions

A major contributing factor to measurement device error is the environment. The cleanliness of the work area that you are conducting a measurement in affects the measurement – and in turn the values that you produce. A variable environment is an inconsistent one, by which the measuring device, can also be influenced. The type of instrument that you are using plays a role in the extent to which it is affected by the environment. For example, an optical instrument will be affected by ambient light. We will take a look at the different types of coordinate measurement devices and instruments in Chapter 4, nevertheless, now we'll continue to look at coordinate metrology principles to be aware of.

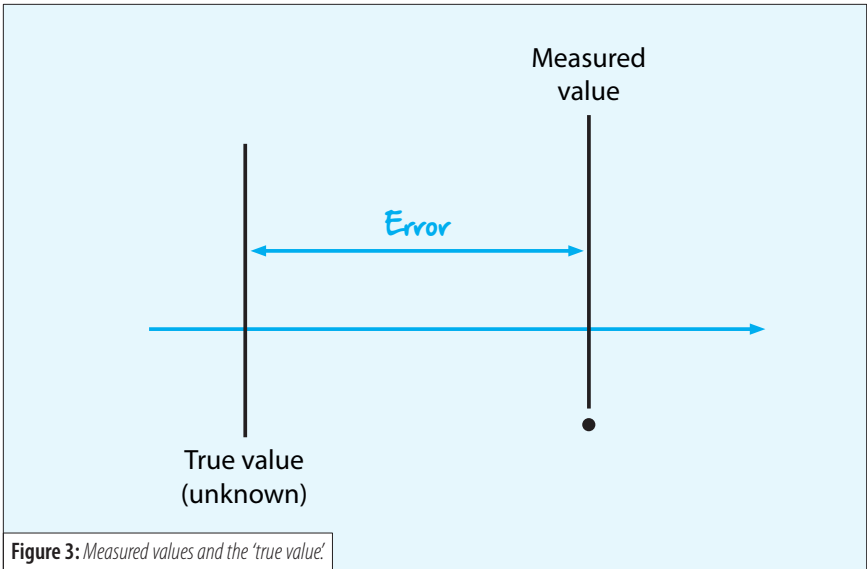
Measurement Uncertainty

No measurement is perfect. *Measurement uncertainty* refers to the level of doubt in a measured value. Measurement is vital to everyday life and ensuring its accuracy is of utmost importance. Measurement uncertainty is always present to some extent, including in the world of coordinate measurement and sources include the measurement devices themselves, the person using them and the processes used to carry out coordinate measurements.

Measurement uncertainty is not the same as error:

- Measurement uncertainty quantifies the doubt in a measured value
- On the other hand, error is the difference between the measured value and true value

The goal of coordinate measurement specialists is not to obtain the correct answer because the true value is unknowable, instead, the objective is to decide on the degree to which it can be tolerated.



Where does uncertainty come from?

Sources of uncertainty include:

- The measuring instrument, which may suffer from ageing, wear and poor readability
- The item being measured, which may not be stable, (e.g. an item may expand in the heat or contract in the cool, dependent on the temperature)
- The measurement process, which may be difficult (e.g. the item may be flexible and unstable, moving within the environment)
- Operator's skill, as the operator's ability, judgement and attention to detail. The operator can measure multiple times, providing repeatability, or more than one operator can carry out the measurement, providing reproducibility
- The environment, as temperature, humidity or other factors may affect the instrument and/or item
- Sampling, the importance of how and when individual features are sampled during the measurement process
- 'Imported' uncertainties, the instrument's calibration has its own pre-existing uncertainties. When using instruments as a user, we inherit uncertainties from the instrument itself

When taking a measurement, you can look at the process and values produced multiples times. Whilst doing so, statistical calculations can be done in order to further investigate the level of uncertainty in a measurement. The two most important statistical calculations that can be done once you have taken a series of measurements are finding the *average* and the *standard deviation* for a set of numbers. The average provides the best estimate of the true value. Standard deviation allows the spread of values to be quantified. It tells us how different the set of values typically are from the average.

What is an uncertainty budget?

An uncertainty budget is defined in the International Vocabulary of Metrology as a 'statement of a measurement uncertainty, of the components of that measurement uncertainty, and of their calculation and combination'.

You can use an **uncertainty budget** to keep track of uncertainty components, and to help you evaluate a total uncertainty. It also helps to identify the areas to concentrate effort in reducing uncertainty.

It often takes the form of a **table**, which can be kept as a spreadsheet. We will take a closer look at uncertainty budgets in the next chapter.

Why is measurement uncertainty so important?

Measurement uncertainty helps us to better interpret results and understand how far measurements are likely to be from the 'true value'. This is particularly important when they are taken for a specific purpose such as calibrating a coordinate measurement instrument for certification. Measurement uncertainty can highlight areas of attention in the procedure or environment and improve accuracy.

Accuracy and Precision

Although accuracy and precision are terms that many may use interchangeably in daily life, in the world of coordinate metrology they are very much distinct from each other.

What is the difference between accuracy and precision?

- Accuracy is a qualitative term describing the closeness of a measured value to the true value
- Precision refers to the dispersion of a number of measurements when repeated.

Figure 4 uses the analogy of hitting a target to represent accuracy and precision, with the centre of the target representing the true value and the four diagrams represent repeated measurements.



Description of measured values

Accuracy and precision

A

- Far from the true value
- Widely dispersed

- Inaccurate
- Not precise



B

- Far from the true value
- Close to each other

- Inaccurate
- Precise



C

- Close to the true value
- Widely dispersed

- Accurate
- Not precise



D

- Close to the true value
- Close to each other

- Accurate
- Precise

Figure 4: Measured values can be either accurate or precise, or both at the same time.

When conducting measurements – bear in mind how accurate and precise the values that you produce are. It's important to think about the significance of both accuracy and precision to your measurements, and to what extent you are willing to compromise on these. Highly accurate measurements may cost more to carry out, so think about the cost vs accuracy trade-off.

Measurement device knowledge

Knowing your measuring device well allows you, as the user or measurement taker, to better comprehend the values that the instrument generates.

Evaluate size/volume requirements

The size and volume of the object being measured has an effect on the choice of measurement device. This is not the only requirement to consider, but it is important to evaluate how to access all the required features with the minimum amount of equipment moves, whilst obtaining the required measurement data and maintaining the required level of accuracy.

Identify appropriate accessories

The most appropriate accessories for an instrument should be used in order to optimise the measurement process. These are the things needed in addition to the measuring equipment. For example, when using a laser tracker, a retro-reflector is used in order to obtain the required coordinates from the object being measured.

Identify ergonomic issues

An instrument's ease of use must be taken into account. Its ergonomic design directly influences usage in manual coordinate measurement processes. How easy or difficult an instrument is to use can contribute towards reducing accuracy and increasing uncertainty within a measurement.

Evaluate material constraints

Instruments are made from a wide variety of materials. From metals, to plastics and composites, each material contains its own properties and characteristics which behave differently under varying measurement conditions.

Evaluate time constraints

It is important to evaluate the time needed to measure an object. Spending an hour on a measurement that only takes ten minutes, or alternatively, spending ten

minutes on a measurement that should take one hour may lead to measurement issues. Therefore, time constraints should be in place. The key here, is to find the most efficient way to measure whereby you are able to reduce time, but not at the expense of accuracy. So, when evaluating how long a measurement will take, ensure that you balance both speed and accuracy in order to avoid producing too much inaccuracy.

For example, a laser scanner moving quickly collects far less information than one that is moving slowly. This is dependent on the parameters that have been set and the speed at which equipment is moved at, contributing to the amount of measurement data that is collected during the measurement of a feature. Here, the amount of data being collected is directly hindered by the extra speed at which the instrument is moving and as a result, the shorter time taken to carry out the measurement.

An automatic instrument on the other hand, has a fixed time. The machine moves and probes the object on its own with a controller. Consistency in the collection of data is more repeatable as it is controlled by the equipment. Nevertheless, evaluating the time available to you and the time needed to measure something and balancing this with speed and accuracy is a key step to take before conducting coordinate measurement.

Evaluate accessibility

Are you able to access what you need to measure? If so, can you measure it all in one go or do you need to reorientate it and measure several sides?

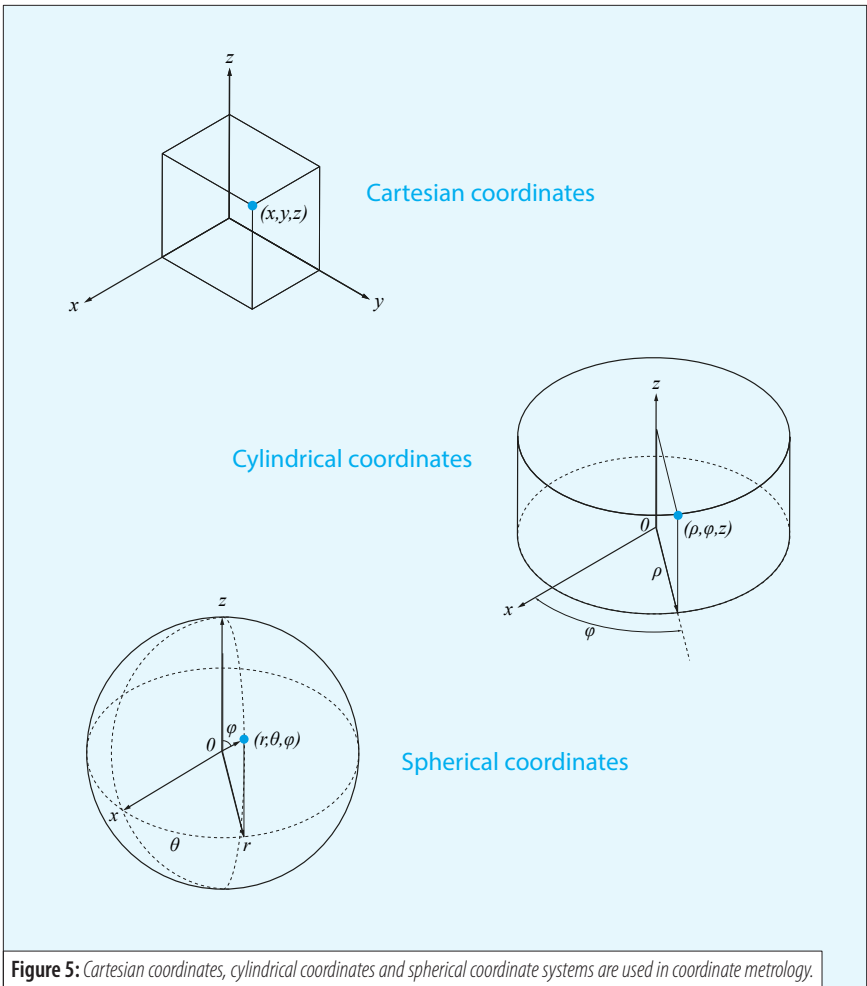
Questions like the above should cross your mind before measuring an object's dimensions. Often, the entirety of the object is not accessible and it may need to be moved during the measurement process. Alternatively, the measurement device may need to be moved. However, how can you ensure that you are getting valid information from both sides of the same object?

An instrument such as a camera will only allow you to see what is visible in its field of view. Using an instrument that can be moved to a different position, perhaps with the help of a robot is an option. For example, a probing system will automatically move around and reposition itself over the top of, but not underneath the object. In most instances, some sort of move will be required on a large object, and then the information is collated to make sense in relation to the design requirements. Yet, it is important to keep in mind that the angles associated with positioning the probe are key, since if miscalculated then there is a chance that the probe could produce incorrect measurement values and even crash.

Types of common metrology equipment

As you may already be aware, coordinate measurement can be carried out using a variety of metrology equipment. Depending on the type of measurements being taken, and the object that is being measured, instruments range from those that require computer control, to those that can be operated by a human. Instruments can also be fixed, as well as portable and can be moved to access difficult to reach parts of an object.

Coordinate metrology equipment commonly work in three different types of coordinates, given in the example below:



Some examples of common coordinate metrology equipment are:

- **Laser tracker** – this device works by directing a laser distance measuring beam at the object, which in turn returns the beam to the tracker. In the example below, the laser beam reflects off the retroreflector which is held against the surface and the two angles and distance value are measured in real time. A tracking mechanism detects any lateral offset of the return beam and keeps the beam on target by rotating it about two axes. 3D values are typically displayed in *Cartesian Coordinates* (Figure 5), but other options exist.



Figure 6: Typical examples of laser trackers.

- **Coordinate measuring machine (CMM)** – a coordinate measuring machine (See Figure 7) is a measuring system with the means to move a probing system and capability to determine spatial coordinates on a workpiece surface. The Coordinate Measuring Machine has its origins in manually operated simple layout inspection equipment. With the invention of Numerical Control (NC) and Computer Numerical Control (NMC) technology CMMs have been developed to be an integral part of both the production and quality departments. There are many different sizes and types of CMMs but they are designed to be in a fixed location where the individuals can take the product to be measured. Over time different probing systems have become available to suit different applications. These systems range from contact to non-contact.



Figure 7: A CMM being used to measure features of size and location

- **Portable coordinate measuring machine** – otherwise similar to traditional CMMs, also known as articulated arm CMMs. They do not move in three orthogonal cartesian axes, they have a number of rotating joints separated by rigid arms that connect the fixed base to the probe. These systems, are manually operated, where the arm is often taken to the product or fixed to a location close to the product or working area. The data is obtained via a contact or non-contact probing system.

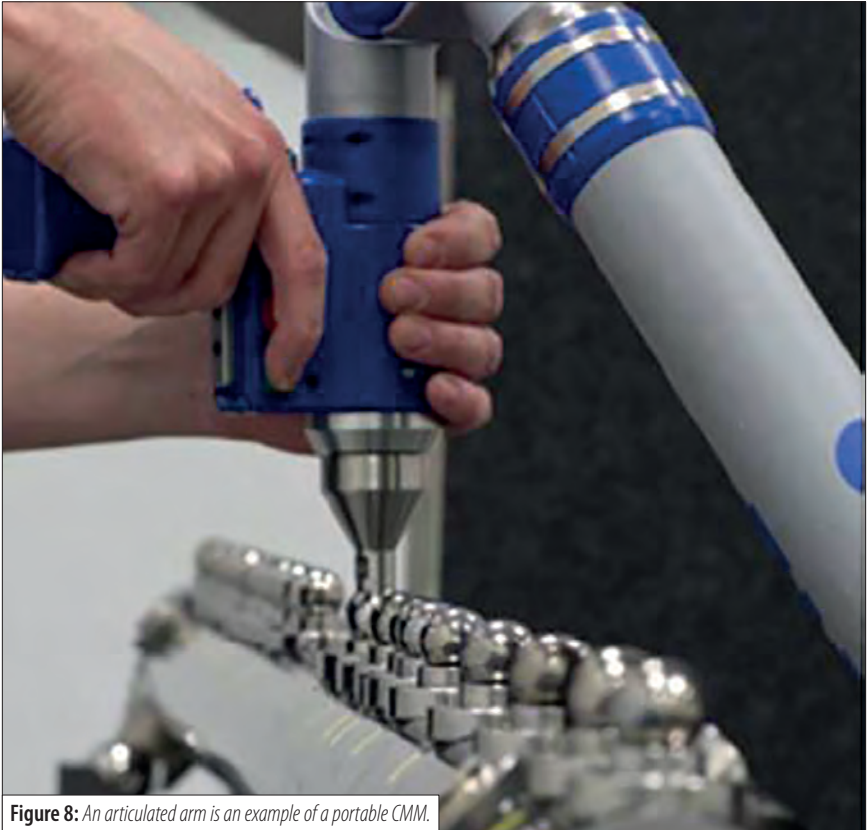


Figure 8: *An articulated arm is an example of a portable CMM.*

In the world of coordinate metrology there are many other types of non-contact equipment being used to measure products and integrate metrology into manufacturing and assembly such as, Laser scanning, Laser projection, Photogrammetric systems, Camera's and X-ray tomography. The world of Coordinate metrology is continuing to evolve.



Figure 9: Coordinate metrology skills testing utilising the five key duty areas at CMSC.



Figure 10: An object being measured using a combination of laser tracker and robot.

Pre-measurement Planning

- Metrology concepts underpinning pre-measurement planning
- Pre-measurement planning

Metrology concepts underpinning pre-measurement planning

Pre-measurement planning is vital to ensuring that a measurement is well thought-through and suitable for the object being measured. We have already looked at the fundamental concepts that support measurement specialists in carrying out a measurement, such as:

- Measurement uncertainty
- Primary standards and traceability
- Units of length
- Environmental influences

These principles allow a measurement specialist to start to compile a measurement strategy. In the first half of this chapter, we will take a closer look at the concept of a measurement strategy. Then, we will move onto on the practical processes to take into account during the pre-measurement planning stage of carrying out a measurement.

Measurement Strategy

There are a variety of questions that need to be asked when creating a measurement strategy. A measurement strategy can be thought of as a structured process of questioning and critical thinking. The resulting decisions are key to a successful measurement. Figure 11 highlights some of the issues that should be considered.

When taking coordinate measurements, there are questions one should be considering. Nevertheless, some questions may become more relevant than others. For example, the type of procedure and instruments to be used may vary significantly depending on the design intent and associated dimensions and tolerances of the object.

What happens without a measurement strategy?

Without a thought process such as that outlined above, the quality of the measurement data is likely to be unsuitable (two types of unsuitable measurements are explained in Figure 12).

An unsuitable measurement can arise when a suitable strategy is not followed when measuring. The balance between accuracy and tolerance is often tested. Higher accuracy than required increases cost, whereas accuracy that is not high enough leads to ambiguity with whether tolerance is met.

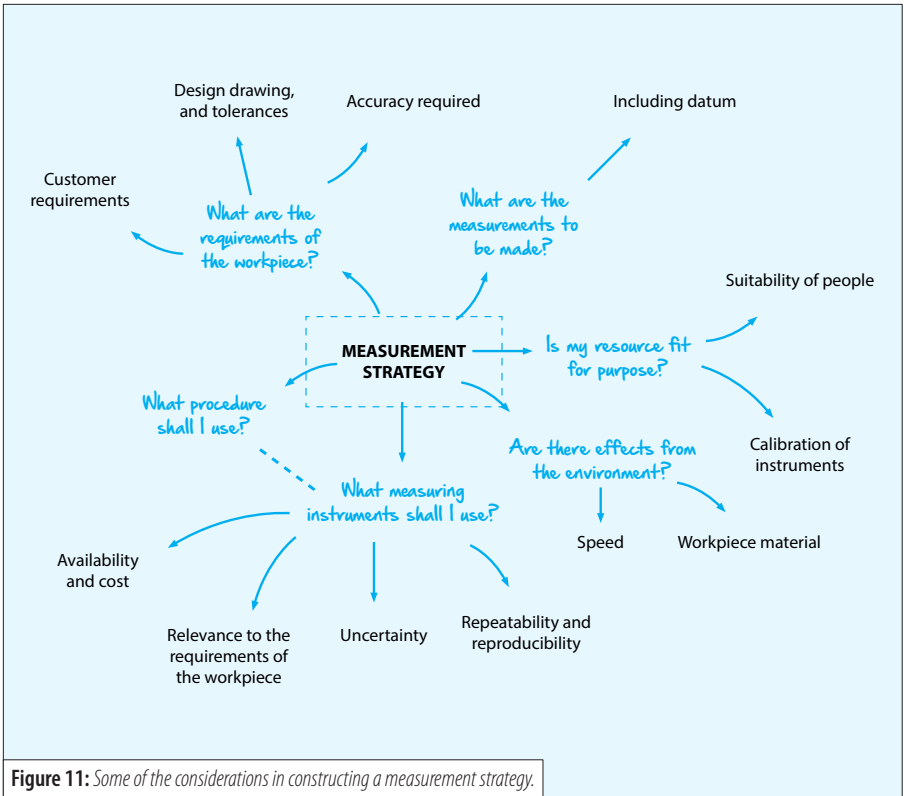


Figure 11: Some of the considerations in constructing a measurement strategy.

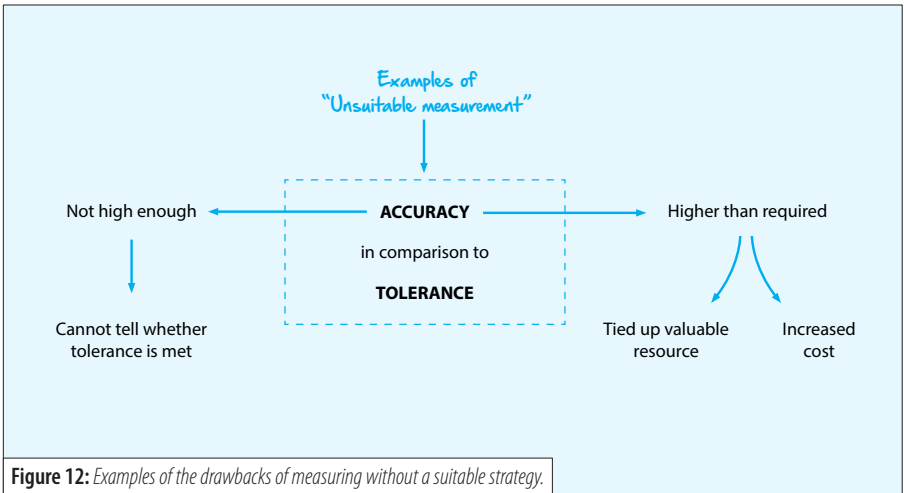


Figure 12: Examples of the drawbacks of measuring without a suitable strategy.

To avoid such unsuitable measurements requires consideration of the principles of measurement listed at the beginning of this chapter.

Measurement uncertainty, primary standards, traceability, and units of length were covered in detail in the previous chapters. Next, we will focus on the fourth concept of measurement: environmental influences.

Environmental Influences

This section explores some of the environmental factors that can affect the value that you obtain in a measurement. Such factors can be called 'influence parameters'.

Measurements of coordinates can be affected by the following factors:

- Vibration
- Draughts
- Temperature changes

Vibration

Vibration can affect measurements of coordinates through effects on the measurement equipment. Vibration can come from many sources, for example:

- Road traffic
- Railways
- Aircraft
- Demolition work
- Activities within the workplace (for example, hammering or machine tools) etc.

Vibration can be minimised using various passive and active anti-vibration devices, such as large seismic masses resting on compliant supports, while pneumatic isolators are used to reduce the effects of vibration, for example, CMMs are often supported on anti-vibration feet.

Draughts

Draughts from doors, windows, factory heaters etc., can also have an effect on your coordinate measurements.

- A door being opened suddenly may cause a rapid change in temperature
- A constant draught on one side of your equipment may cause a thermal gradient with the result that your equipment and the part distorts

The easiest solution is to stop the draught at its source. If this is not possible, then putting the equipment in a suitable enclosure can help in some instances.

Temperature

Finally, coordinate measurements can also be affected by the influence of temperature on both the object being measured and the measuring system itself. In fact, this can be one of the largest sources of error in a measurement process.

Most materials expand as they are heated, and contract when they are cooled.

Different materials expand by different amounts for a given temperature rise.

The coefficient of linear thermal expansion quantifies the fractional change in length per degree of temperature change.

Table 4 shows coefficients of linear expansion for some materials commonly used in manufacturing.

Some coefficients of linear thermal expansion	
Material	Coefficient of linear thermal expansion / $10^{-6} \text{ }^{\circ}\text{C}^{-1}$
Aluminium	23.6
Steel	11.6
Invar	1.0
Tungsten carbide	4.0
Brass	20.0
Copper	16.0
Bronze	18.4
Titanium	8.4

Table 4: The coefficient of linear thermal expansion is the fractional change in length per degree of temperature change.

Looking at Table 4, you can see that:

- Aluminum expands most for a given temperature change
- Invar is comparatively stable in length with respect to temperature changes (this is one reason why it is used in precision measuring tapes)

The unit of linear expansion coefficient means ‘parts per million, per degree Celsius’, so that copper, for example, expands by 16 parts per million for every degree Celsius it is heated up. For example:

- A 1m copper bar will expand by 16 micrometres when its temperature increases by 1 degree Celsius
- The same copper bar will expand twice as much for double the temperature rise
- A 2m copper bar will expand by 96 micrometres when its temperature increases by 3 degrees Celsius

Because the size of an object depends upon its temperature:

- Dimensions on technical drawings, unless otherwise stated, apply to 20° Celsius
- Compensations should be applied if the actual temperature of an object is different from this reference temperature

Pre-measurement planning

A key part of pre-measurement planning is a practical framework for the measurement procedure, taking into account the concepts discussed above.

This practical framework enables consistent, precise and traceable measurement practices to take place. Such guidelines ensure good application of the scientific principles mentioned in this guide.

Let’s take a look at the practical steps involved.

Determine uncertainty budget

As mentioned in the previous chapter, uncertainty budgets are used to keep track of uncertainty components, and to help you evaluate a total uncertainty. It often takes the form of a table. Table 5 illustrates a typical uncertainty budget.

Source of uncertainty	Uncertainty value	Probability distribution	Divisor	Sensitivity coefficient	Contribution to combined standard uncertainty

Table 5: *The layout of a typical uncertainty budget.*

We have already seen that the overall uncertainty associated with the final measured value is usually a result of a combination of several individual effects. When carrying out coordinate measurements, evaluating the level of uncertainty can be done by taking into account these individual sources of uncertainty. Such sources include equipment and the application of equipment.

As can be seen from Table 5, an uncertainty budget has a number of columns. The purpose of these columns can be summarised as follows:

- The 'Source of uncertainty' column describes each individual effect that contributes to the overall uncertainty
- The 'Uncertainty value' column gives the value of the uncertainty associated with an individual effect
- The 'Probability distribution' column contains information on how the source of uncertainty affects the resulting spread of the measured values
- The 'Divisor' is used to make the uncertainty values comparable (they are then called standard uncertainties) so that they can later be combined. The value of the divisor depends on the probability distribution
- The 'Sensitivity coefficient' describes the extent to which the source of uncertainty influences the measurement result
- The first five columns are used to calculate the 'Contribution to the combined standard uncertainty'; this gives the final contribution from a given source of uncertainty to the overall uncertainty

Once obtained, the 'Contributions to the combined standard uncertainty' from the last column can be combined, and an expanded uncertainty can then be evaluated.

Optimise equipment stations

It's important to plan out the best way to locate equipment and parts being used for the measurement beforehand. By optimising equipment stations, measurements can be made more efficient. For example, minimising the number of changes in position and amount of set ups required will allow a smooth and thought-through measurement to be carried out.

Determine data collection

A key part of pre-measurement planning is to correctly identify what it is that you are measuring. Determining the data collection process and ensuring that you are aware of what coordinates you are most interested in will direct your measurements. Understand the particular features and products to be measured and how many times they must be measured. Measure features in an order that allows the most efficient strategy possible.

Plan reference system

Planning the reference system refers to defining the coordinate system being used to obtain the correct coordinate measurements as defined by the drawing or CAD model. Good practice before a coordinate measurement is taken is to understand and plan the complete setup of the coordinate systems required, in relation to the design or application requirements being followed.

Determine order of measurement

Pre-measurement planning involves determining the order of coordinates being measured. Plan the order of measurement in an efficient manner to reduce the number of setups required. This also saves time and money, and can provide a buffer for unforeseen delays.

Estimate data collection time

A good estimate of data collection time is important to consider during the pre-measurement phase of coordinate measurement. Understand how long is needed to measure and collect sufficient data. Resist cutting corners or skipping steps in the measurement process — this can lead to data inaccuracy and produce values that do not represent the object being measured.

Determine naming conventions

Identifiable features are often named for easier data collection. However, when choosing these names, determine naming conventions that make sense in the context of the measurement plan.

Identify safety requirements

There may be safety requirements concerning equipment, location and the object being measured. Before taking a coordinate measurement, look at the size and weight of the object, whether the environment has sharp edges or hanging objects, and whether safety precautions can be put into place such as wearing a hard hat for example.

Plan coordinate systems

What kind of coordinate system will you be using? Plan this beforehand. Perhaps you have more than one set up to prepare for. If so, plan the order, priority of each and an efficient method of carrying out these coordinate systems.

Plan traceability and documentation

How do you ensure measurements are traceable? This can be done through calibration and relevant calibration certificates, as well as traceable artefacts.

Calibration underpins measurement traceability. As we saw in Chapter 1, traceability gives us confidence that the measurement instruments we use give accurate results.

A Certificate of Calibration contains any associated details that are needed to have confidence in the measuring equipment being used.

Information contained in a Certificate of Calibration includes:

- Calibration results
- An endorsement from an accreditation laboratory for the calibrations performed
- Details of the method used for calibration
- The name and address of the laboratory
- The location at which the calibration was carried out
- The customer's name and address
- The calibration uncertainty
- Traceability information

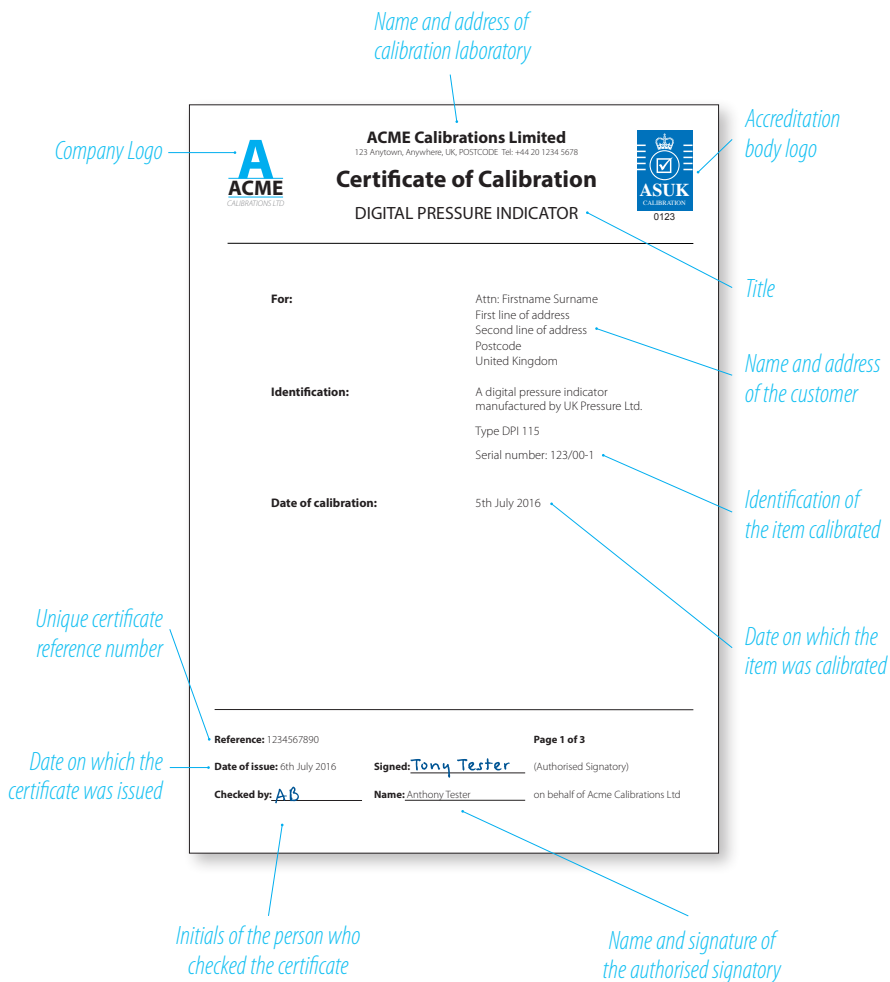


Figure 13: A representative example of the front page of a calibration certificate

Traceable artefacts, also referred to as reference artefacts have a property that is known to a suitably high level of accuracy. For coordinate metrology applications, this property is usually a length or size. For example, when you calibrate a micrometer with a gauge block, the gauge block is acting as a traceable artefact. Bear in mind that the gauge block itself must be calibrated.

When dealing with coordinate metrology equipment, different reference artefacts are available to use in order to calibrate or verify the performance of said equipment. Where possible, it is good practice to make interim checks on the equipment prior to use, against the reference artefacts.

Create a documentation plan

Outline all of the steps involved with carrying out your particular coordinate measurement in the form of a documentation plan. This detailed plan will allow you to keep a record of activities to be carried out and the order in which they need to be done.

Plan subject temperature compensation strategy

A temperature compensation strategy allows for unpredictable external influences on the measurement subject. Where possible, check the temperature compensation requirements of the equipment being used and enter any relevant data into the software. Sometimes, it is not easy to determine if the product and equipment is going to move in a uniform way due to environmental influences. Do not forget that temperature is only one of a variety of influences that can contribute to variation, such as humidity, lighting, dust and pressure.

Maintain equipment

The equipment that you plan to use during your measurement must be maintained. It is important to be aware of what things need to be done before, during and after the measurement with your equipment – so that it works as it should and is not susceptible to damage or mishandling. In addition, be careful not to damage the equipment whilst using it to take measurements.

Performing Measurement Operations

- Verification of calibration status
- Setup equipment
- Perform *in-situ* equipment check
- Install reference features
- Mitigate environmental influence
- Measure features of interest
- Re-check reference features
- Perform device move if required
- Perform quality assurance of data set
- Manage measurement data
- Establish traceability

In the previous chapters, we discussed the relevant metrological concepts in coordinate measurement. This chapter will discuss the actions involved in carrying out a measurement and what operational considerations are to be followed.

Verification of calibration status

Before using any equipment, check that it has been calibrated by the original equipment manufacturer or trusted service company. A calibration certificate (discussed in Chapter 4) will provide assurance that this has been done. A certificate is issued based on the results of successful calibration. It will usually be a multi-page document comprising of a front page and more continuation sheets.

Setup equipment

The way in which your equipment is setup plays a central role in the measurement that you are taking. For example, if the equipment requires locating on or in a stand then how and where this is fixed is important.

Set up your equipment in a manner that does not block the line of sight that you are interested in. Keep in mind what is accessible to the instrument and whether the setup needs to be adjusted before, or moved during the measurement process.



Figure 14: *Stands and where they are fixed play a large role in setting up measurement equipment.*

Perform *in-situ* (field) check

It is important to monitor your equipment whilst performing measurement operations. Performing *in-situ* equipment checks ensure that they are functioning correctly. It also alerts the measurement specialist of any actions to be taken, if necessary. Occasionally, replacing the instrument or ancillary may be required.

Install reference features

Reference features are artefacts that can be added to a fixture or a part being measured, so that a datum system can be established from these features.

A datum system is made up from features or reference artefacts to define the coordinate system to be used when measuring.

Measure reference features to create a coordinate system

By measuring the reference features now installed, a *coordinate system* can be established. Once created and confirmed, the part is located and orientated for the remainder of the part features to be measured and reported.

Mitigate environmental influence

Understanding how the environment impacts your equipment can help with avoiding any issues arising. Be aware of the effect a current condition such as temperature change can have on your measurements. For example you may be required to measure a part in conditions where the effects of lighting, sunlight and pressure may cause changes in the measuring equipment.

Taking into account and managing the temperature of the environment, and the degree of influence that it has on the part being measured, is a key part of good measurement practice.

Where appropriate and feasible, use the coefficient of linear thermal expansion — (as discussed in the previous chapter) — to compensate for temperature differences from the reference temperature.

Measure features of interest

On completion of all the requirements in the previous section, it is now time to measure all the features of interest to determine if the product conforms to the design requirements. This may include features of form, location, orientation and profile. Being aware of the quality of the data being collected from each feature is important. As is, being able to identify where bad measurement points have been measured and what to do to rectify them.

Re-check reference features

It is important to be confident in the quality of the data obtained in order to establish the coordinate systems. By rechecking the reference features, confidence in the data obtained from the features of interest can be established and reported if required.

Errors can arise when setting up from reference features. Re-checking reference features ensures that the coordinate system created from them is reflective of the measurement you intend on taking.

Perform device move if required

Moving the measuring device allows the measurement specialist to generate optimal outputs. By moving equipment in line with areas of interest that are not visible, you are able to access these features more easily.

However, bear in mind that the number of device moves should be kept to a minimum. There is always a risk that errors will be introduced when re-establishing the coordinate system.

Perform quality assurance of data set

It is important to determine the quality of information that you are gathering during the measurement process. Is the data of good value?

Perform an initial assessment of the data, for example examine the goodness of fit of features to measured points to look for anomalies. Where anomalies are identified, re-measure the features and check the data again.

Manage measurement data

Now that you have completed the measurement process and collected sufficient data, it needs to be managed.

Firstly, process the data. Then, compare the measurement data to the design specifications. Produce any required reports and then output the data in the required format to the appropriate individual, department or customer.

Lastly, compare your measurement data to the design specifications. This gives you a good idea of how closely, or how far, your measurement data compares to those listed in the design requirements.

Establish traceability

As discussed in previous chapters, traceability gives confidence that the measurements made are accurate representations of the item being measured.

In order to establish traceability, an unbroken chain of calibrations is required – leading all the way back to primary standards. Mentioned earlier in this guide, this is known as a ‘traceability chain’.

It is important to establish the traceability of the measurements to give confidence in the quality of the data. Traceability requires that a measurement uncertainty is ascribed to the measurement results.

Analysing Data

- Compare measurement data to design specifications
- Combine and evaluate alignment
- Register data sets to reference system
- Optimise data
- Construct geometry
- Calculate uncertainty and its impact
- Statistical techniques and calculations

Now that we have outlined each of the key duty areas to follow before and during the coordinate measurement process, the sixth and final chapter in this Good Practice Guide will focus on the duty area concerned with the analysis of data.

Compare measurement data to design specifications

Comparing the measurement data to the design specification is sometimes completed during the measurement process, or alternatively, analysed at a later stage. This means checking your measurement results against the tolerances – either on a blueprint or CAD model.

Once you have done this, you can then make an informed decision to either accept or reject a part.

Evaluate GD&T

Evaluating the GD&T, or Geometric Dimensioning and Tolerancing, is an important part of comparing to design specifications. Discussed in Chapter 1, GD&T documentation defines and outlines engineering tolerances.

These tolerances are communicated using symbols on engineering drawings and computer-generated models, which describe the geometry of an object. Evaluating the GD&T specified for the object that you are measuring, is important to gain an understanding of how closely the measurement results gained reflect the sizes, geometries and tolerances necessary.

Combine and evaluate alignment

It is important to consider the alignment of your measurement values. Understanding the quality of the alignment is possible once all measurement moves have been combined into one. The measurement specialist does this by collecting multiple sets of measurements from different areas of a part and then combining them together into one set.

For example, in the case of an aircraft, this would involve:

- 1) Measuring an aircraft from different positions
- 2) Combining the data
- 3) Evaluating how good the alignment of the data is

Register data sets to reference system

Once the data has been combined and evaluated, it is important to register these to a reference system.

Collect the data from various places and then combine them as one, before linking it to the part or the assembly's datums or coordinate system.

Optimise data

Optimising the data is carried out in order to check its validity. Make sure that the values recorded are the best possible values that can be achieved by the measurement procedure being used. By optimising the data, you should be able to see how the measurement data can be fitted into the required specification using the techniques which best suit this.

Construct geometry

Constructing the geometry of the object that you have measured allows a picture to be painted of it. Build up geometric features from data that has been collected from the part.

This can include intersections, 2D and 3D distances and angles between features.

Calculate uncertainty and its impact

As discussed in Chapter 3, determining the overall uncertainty of a measurement allows the level of doubt in the measured values to be quantified.

Calculate the uncertainty and identify the major contributors to this. Examples of sources of measurement uncertainty include the measuring instrument, the item being measured, the measurement procedure and the skill of the operator.

The impact of measurement uncertainty is unique to each measurement. The extent to which it affects the measurement process will vary.

Statistical techniques and calculations

As mentioned in previous chapters, statistics allows us to learn more from measurement values and to get a better estimate of the true value. As a reminder, fundamental statistical techniques and calculations include:

- **Mean:** the average of a group of varied results. This is done by adding the values together and dividing the result by the total number of values
- **Range:** the difference between the highest and lowest value in the data set. First, order the data from least, to greatest, before subtracting the smallest value from the largest
- **Standard deviation:** allows the variation in values to be visualised. It tells us how different values typically are from the average. (To learn more about standard deviation and calculation, refer to NPL's *Good Practice Guide No 11: An introduction to uncertainty of measurement*)

The data acquired from such calculations can be visualised in graphs such as a histogram, normal distribution curves, control charts and Measurement Systems Analysis techniques.

Conclusion

During the course of this guide, the key duty areas to follow when carrying out a coordinate measurement were discussed. This document was designed for anyone who requires to strategically plan for coordinate metrology.

The overarching goal of this document was to ensure that better measurements are made. By learning about the core concepts of metrology before addressing the steps taken in coordinate measurement, you should now have a good understanding of how the two relate to each other. The links between design, manufacturing and measurement will have become evident to you as each chapter progressed.

Coordinate metrology underpins much of everyday life and industry. Now that you have gained an understanding of the metrological knowledge that it is built upon, this will prepare you for additional material on the subject. In particular, focusing next on the practical methods involved with carrying out coordinate measurements.

References & further reading

- References
- Further reading
- Contact NPL

References

1. The International Vocabulary of Metrology (2008), *Basic and general concepts and associated terms* *Platinum Metals Review*, **7** (3), p.93
2. Schöenberg, S & When, A, (2016), Industrial automated laser tracker application, *The Journal of the CMSC FFT Produktionssysteme*, **11** (1), p. 8
3. Rosenberg, E, (2016), The uses and deployment of large-volume laser scanning, *The Journal of the CMSC, ECM Global*, **11** (1), p. 16

Further reading

1. For more information on Chapter 1 and 6: Bell, S A, (2001) *A beginner's guide to measurement, Measurement Good Practice Guide No. 11*
2. For more information on Chapter 2, 5 and 6: Flack, D R, Bevan, K, (2005) *Fundamental good practice guide in the design and interpretation of engineering drawings for measurement processes, Measurement Good Practice Guide No. 79*
3. For more information on Chapter 3: *National Physical Laboratory, Dimensional Measurement: Measurement User, e-Learning programme*
4. For more information on Chapter 4: Flack, D, (2014) *CMM measurement strategies, Measurement Good Practice Guide No. 41*
5. For more information on Chapter 4 and 5: Flack, D R, Hannaford, J, (2006) *Fundamental good practice in dimensional metrology, Measurement Good Practice Guide No. 80*
6. For an introduction to metrology: *National Physical Laboratory, Certified introduction to metrology, e-Learning programme*
7. For an introduction to measurement uncertainty: *National Physical Laboratory, Certified introduction to measurement uncertainty, e-Learning programme*

Contact NPL

National Physical Laboratory

The National Physical Laboratory (NPL) is the UK's National Measurement Institute. The heart of our mission is to deliver science with impact by disseminating research and measurement best practice for economic and social benefit.

National Physical Laboratory
Hampton Road
Teddington
Middlesex
TW11 0LW

Switchboard **020 8977 3222**
www.npl.co.uk/contact

Keep in touch with us

Sign up to receive regular updates:
www.npl.co.uk/keep-in-touch

Follow NPL on Twitter:
www.twitter.com/npl

Become a Facebook fan:
www.facebook.com/npldigital

Subscribe on YouTube:
www.youtube.com/npldigital

Follow NPL on LinkedIn:
www.linkedin.com/company/national-physical-laboratory

Strategic Planning for Coordinate Metrology

Good Practice Guide No. 138

What is it about?

This document was designed for anyone who requires to strategically plan for coordinate metrology. Written in collaboration with the Coordinate Metrology Society, the information provided in this Guide is intended to complement the Coordinate Metrology Society Conference (CMSC).

Who is it for?

This guide is for users who want to gain familiarity with the fundamental principles of coordinate metrology in the context of dimensional measurement. It is designed for anyone who requires to strategically plan for coordinate metrology.

What is its purpose?

The purpose of the guide is to provide underpinning metrological knowledge, focusing on coordinate metrology in particular, in order to promote good practice when using portable coordinate measuring systems.

What is the prerequisite knowledge?

This guide is at entry/intermediate level and it does not assume any specific background knowledge.