Simply measure

And what you should know to do it right

A metrology primer

Carl Zeiss 3D Metrology Services

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Foreword

About this primer

This primer was prepared for anyone who works with coordinate measuring machines and measuring software and would like to learn the basics required for that purpose.

Its contents include:

- Chap. 1 From caliper gage to CMM

  Why can neither caliper gages nor further developed single-purpose measuring techniques meet the demands of modern mass production? How does a CMM work?

- Chap. 2 From scribing to form measurement

  Survey of different types of CMMs and their range of application.

- Chap. 3 From probe tip to program - path of the measuring data

  Which components of the CMM jointly determine the probing location?

- Chap. 4 From vector to projected angle

  Just the very basics of the mathematics involved - so that you know what you're measuring and what the values output by the CMM really mean.

- Chap. 5 From probing to measuring result

  What happens to the "raw measuring data" - how do the probe, the probe tip radius, the probing direction and systematic deviations figure into the measuring result?

- Chap. 6 What does CALYPSO actually do?

  What do "inspection characteristic" and "measured element" mean in CALYPSO?

- Chap. 7 From planning to evaluating results - where am I?

  What phases and stages are involved in the utilization of a coordinate measuring machine?

For your convenience...

...this primer contains a glossary. A **glossary** is a concise dictionary used to explain various individual terms. You mainly need the definitions it contains where the corresponding terms actually appear. And that's the reason why our glossary has been divided into sections located next to the terms it defines throughout the following text.

? Glossary

A glossary describes terms briefly and succinctly.

Foreword

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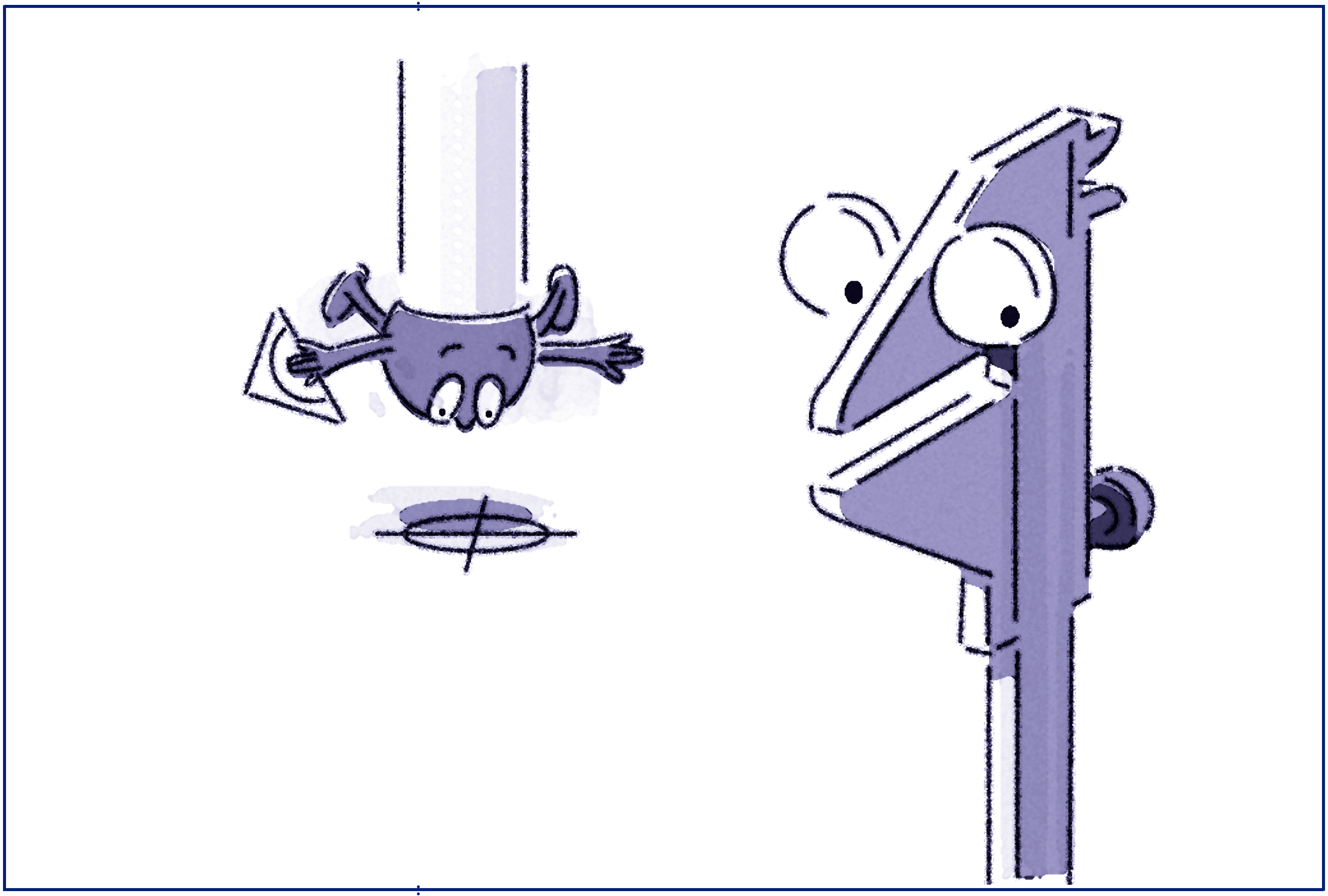
1

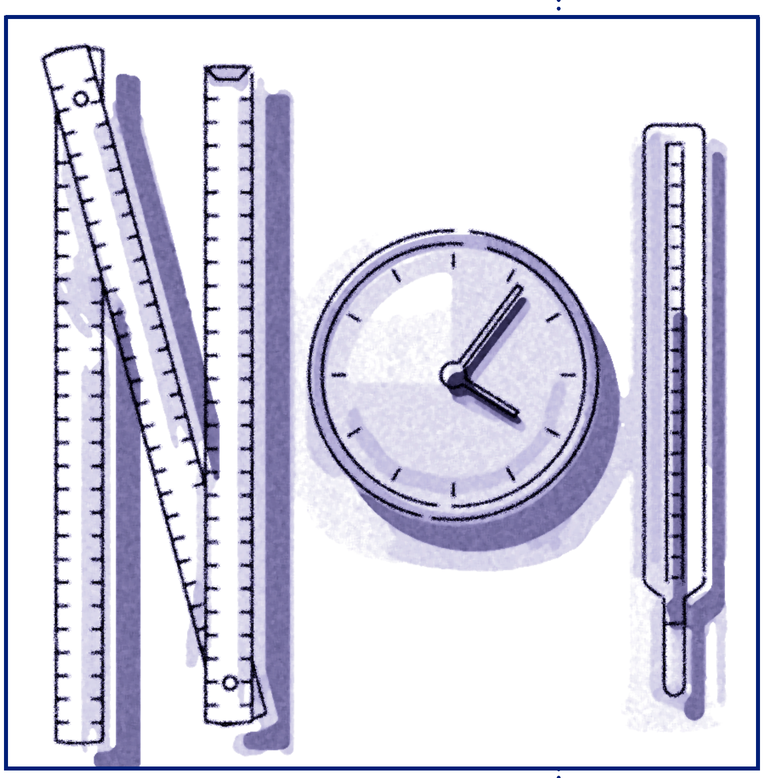
From caliper gage to CMM



In this chapter you will first read about measurement using the "good old caliper gage". Why can neither the caliper gage nor more advanced single-instrument measuring techniques satisfy the requirements of modern mass production for high-precision machined workpieces?

What is the basic principle of coordinate metrology and what advantages does a coordinate measuring machine offer in comparison to other measuring instruments?

Measuring with the caliper gage



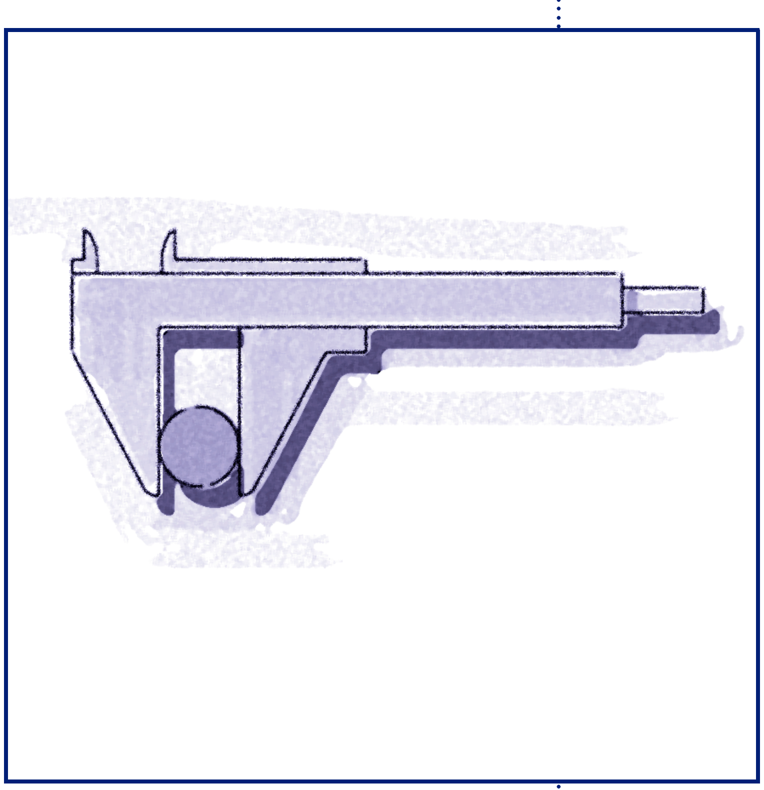
Why measure?

All of us are constantly involved with measurement. Every time you look at a clock, check the temperature reading on a thermometer or count your money you're measuring values or reading the results of measurements in one form or another.

In any case, what measurement really involves is comparing something with the most precise model or scale available. This becomes especially clear if we measure an object's length by placing a scale next to it.

By the way: constantly improved methods of comparison using increasingly precise models or scales is the basis for technical progress. Because it is difficult at best (and sometimes even impossible) to assemble products or interchange parts without reliable models, exact measurements and defined standards. An effective division of labor would also prove impossible. Furthermore, a technical product or activity can be evaluated and therefore influenced only by means of measurement.

Technical progress in turn enables increasingly improved, more accurate and more convenient measurement technologies.



The caliper gage

The "good old caliper gage" characterized a relatively long period of industrial and commercial technology. Generations grew up using this instrument.

The caliper gage is based on a fundamental principle: the distance between two points is the value to be measured. This is done by sliding one scale along another one and "probing" two points, thus setting the scale to a position which corresponds to the actual distance between the two probed points.

The distance between the two points can be measured in an order of magnitude more exact than the naked eye could discern by comparing the slight deviation between the two scales.

What the caliper gage can not do

On the other hand, no further increase in accuracy can be achieved using this technique. Another method must be employed if, as is often the case, we need more exact data.

Furthermore, insufficient accuracy is not the only deficiency of the caliper gage.

- Another shortcoming is the one-sidedness or lacking flexibility of its "data output". Other dimensions, e.g. angles, must be calculated separately. Furthermore, many values required to assess a workpiece can neither be measured directly nor derived from the measured length.
- The size and shape of the caliper gage set certain limits: particularly small or intricately designed, filigreed workpieces and exceptionally large objects can not be measured with a caliper gage.
- In addition, the shape of its jaws automatically excludes "probing" certain points from the start.

A very large number of more modern, more accurate and more flexible measuring devices have been invented since the introduction of the caliper gage. Unfortunately, none of them can overcome all of the shortcomings listed above. Furthermore, all of them fail to meet the demands placed on metrology by modern mass production.

Demands placed on modern metrology

CNC

*Abbreviation for "***C***omputer* **N***u-merical[ly]* **C***ontrol[led]". Refers to methods of production and measurement in which the machines are controlled by numeric data and programs.*

Products manufactured on modern assembly lines can no longer be inspected with a caliper gage. Even special gages custom-made for the workpiece being checked are not suitable for this purpose, since they become inappropriate as soon as the product is modified only slightly or another product is produced.

Particularly **CNC** production, flexible manufacturing systems and non-cutting methods of manufacture place new demands on measuring control regarding setup and routine production operation.

What must measuring instruments be able to do?

What kind of measuring instruments are required for modern metrology? These instruments must:

- be fast
- perform automated operation
- be able to directly measure or calculate a very wide variety of dimensions, derived values and quality characteristics
- be able to measure small, medium-size and large workpieces with a basic or an elaborate design
- be flexibly adaptable to new requirements
- be relatively easy to operate
- operate with high reliability and repeatability.

No traditional, conventional measuring device can satisfy all of these demands: Not only caliper gages, but also gages of every type and design, precision dial gages, height gages and multipoint measuring devices simply can not "fill the bill" here.

The consequence: a CMM

Coordinate Measuring Machine

A coordinate measuring machine determines the position of random spatial points and outputs them as coordinates.

All of the requirements specified above are fulfilled by a single instrument which "*merely*" measures the position of random points extremely accurately (but not the distance between two random points) and evaluates the data acquired or forwards it for evaluation: i.e. by a **coordinate measuring machine** (CMM).

What a CMM can do

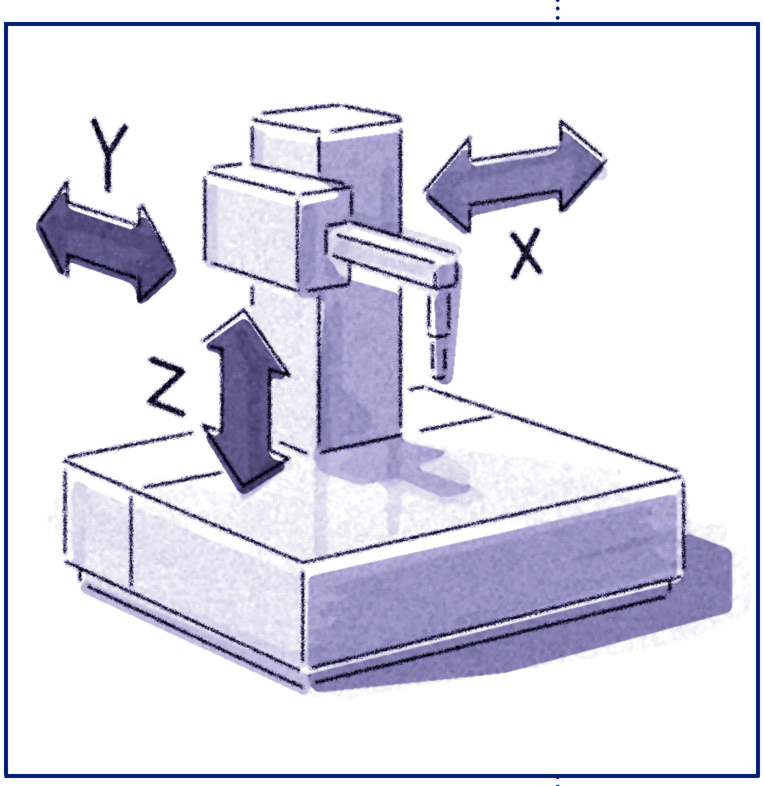
The principle of coordinate measurement basically offers two advantages:

- *Derived data and evaluations*

  Virtually all of the dimensions required to evaluate the dimensional accuracy and quality of a workpiece can be calculated and derived from the exact data of randomly probed points.

- *Scanning function*

  Machines equipped with measuring probe heads feature an additional capability: they can also be used to inspect geometric shapes by probing (or scanning) as many points as possible in a dense grid. A grid model of the surface, and therefore of the body, can be acquired in this manner. This function can be used for quality assurance as well as for design and development.



Overcoming limits to accuracy

In the accuracy class involved here, long familiar physical effects suddenly take on new significance: differences in temperature and (even slight) weights alter the shape of the CMM and the workpiece (through bending, stretching and compressing) or its reactions in such a way that the measurement is falsified.

What can be done? These influences must be minimized and the unavoidable residual error must be taken into account as far as possible.

How high accuracy is achieved

The conditions necessary for the required accuracy have been achieved through new technological developments:

- Hardware-related improvements include high-precision opto-electronic measuring systems, low-friction air bearings and materials offering maximum mechanical and thermal stability (e.g. CARAT ceramics and carbon fiber).

However, development remains an on-going process; new materials and measuring techniques are constantly being invented.

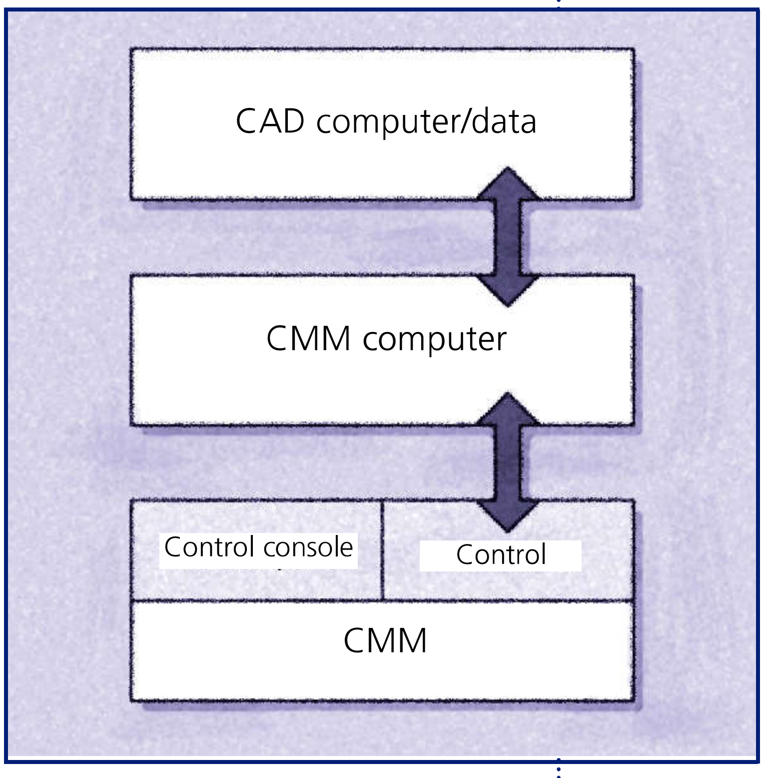
- Software-related advances include techniques and programs which automatically take measurement corrections into account during operation without human intervention.

  These comprise both the correction of systematic, machine-related falsifications of measurements and (as one of the latest developments) the measurement and automatic consideration of minimal heat currents in the base.

Processing the results of measurements

In addition to the advantages mentioned above, it should also be noted that the basic principle of coordinate metrology is very suitable for computer-aided setup of the CMM and processing of the measuring results.

The control in the CMM ...



Every coordinate measuring machine also includes an electronic control. This "control computer" is used e.g.:

- to calibrate the CMM
- to control the CMM during automated measurement or scanning runs.

... and the CMM computer

The CMM is connected to a computer, i.e. your PC or workstation, via an interface. If equipped with the appropriate software, this computer can:

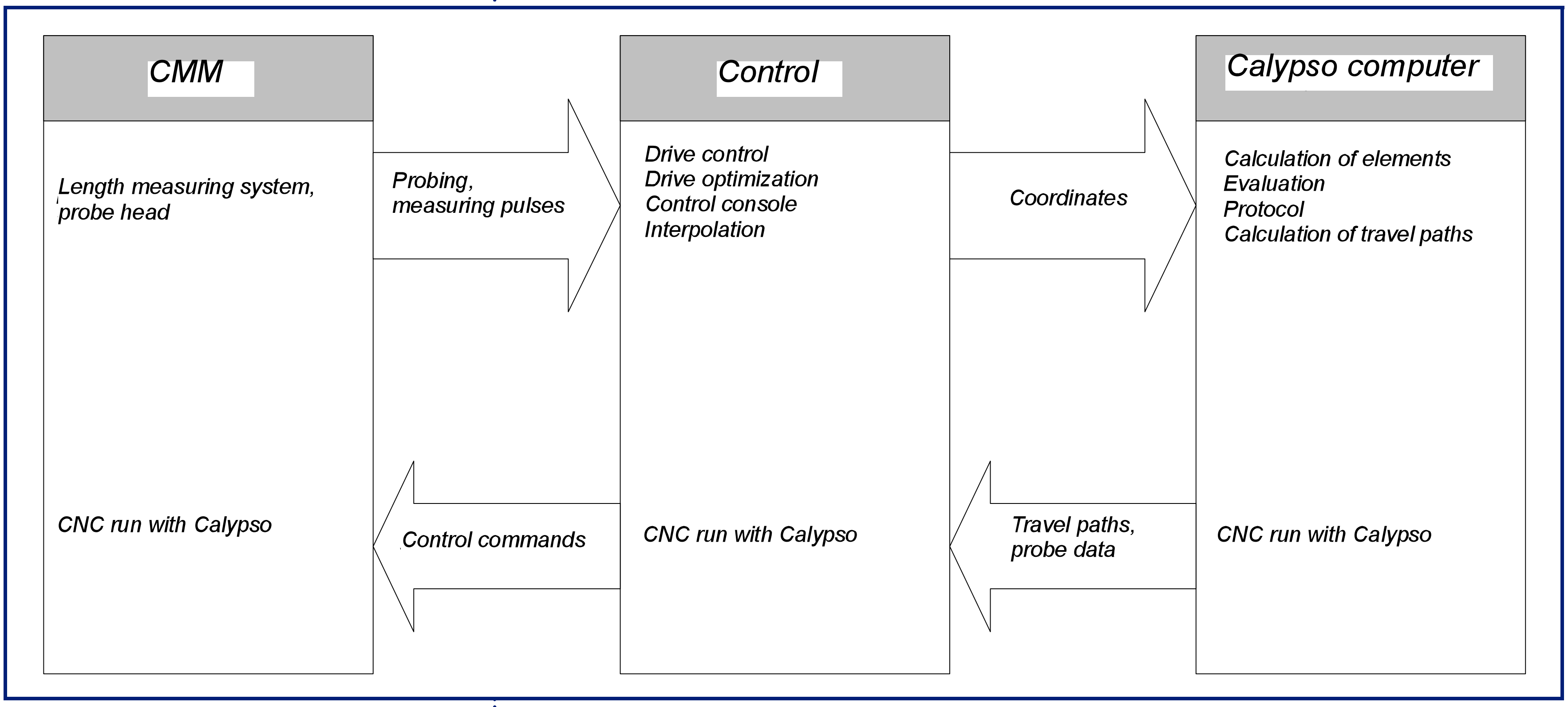
- correct the acquired measured values
- convert from one coordinate system to another
- calculate derived dimensions (points, lines, angles etc.).

The operation of the CMM is thus simplified from data input to control and the results can be evaluated and documented in many different ways. Via CALYPSO; a model of the workpiece to be measured can also be graphically displayed on the viewing screen (in a 3D view).

Quality inspection can be simplified and automated even further e.g. by accessing CAD workpiece data stored in the company network.

Interplay of components

The following illustration gives you an overview of the information exchanged between components of the CMM and the CALYPSO computer and the functions of the individual parts. For more details, see the following chapters.



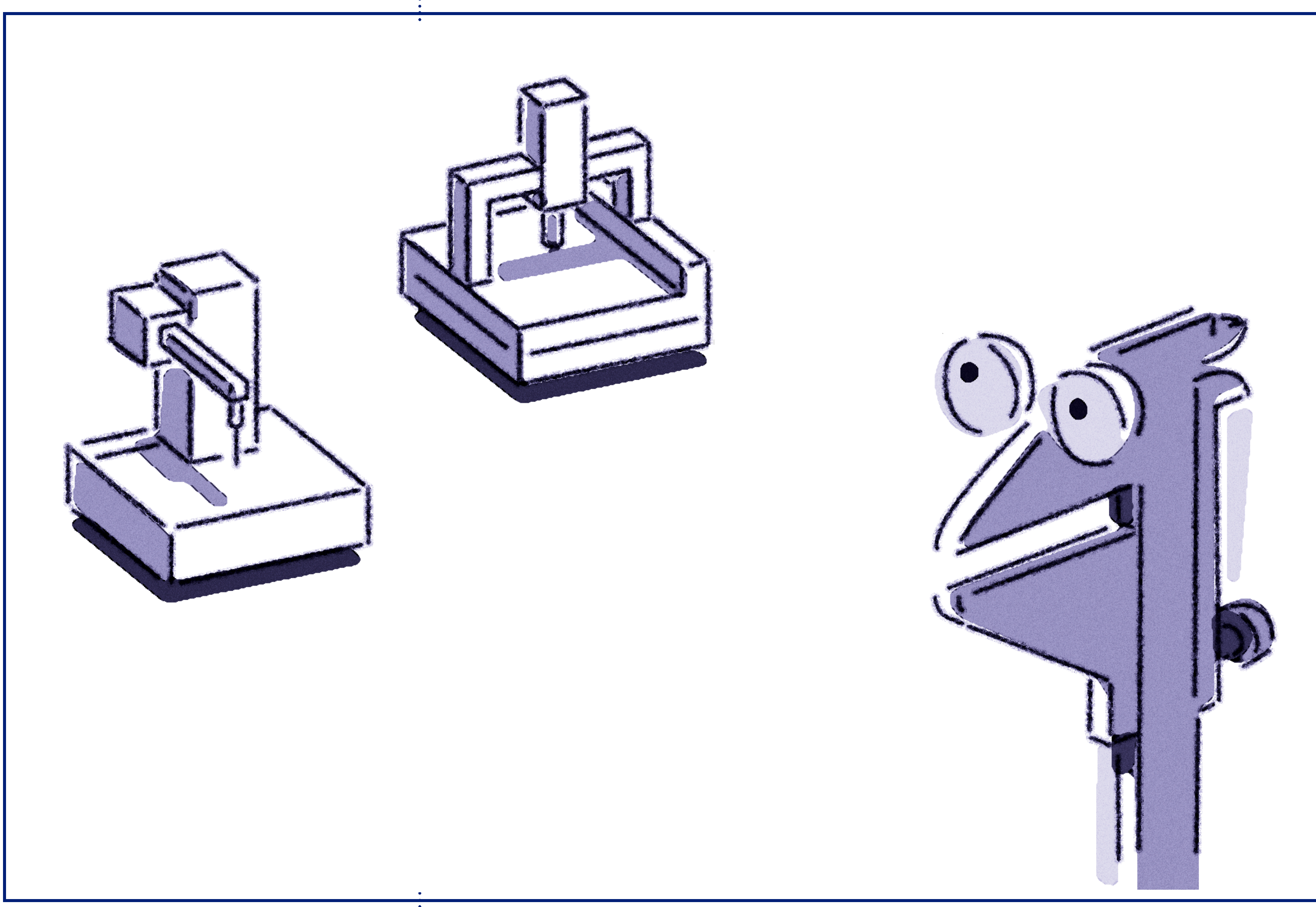
What you should know now

Why can caliper gages no longer satisfy the demands of modern mass production?

What are the advantages of a coordinate measuring machine?

2

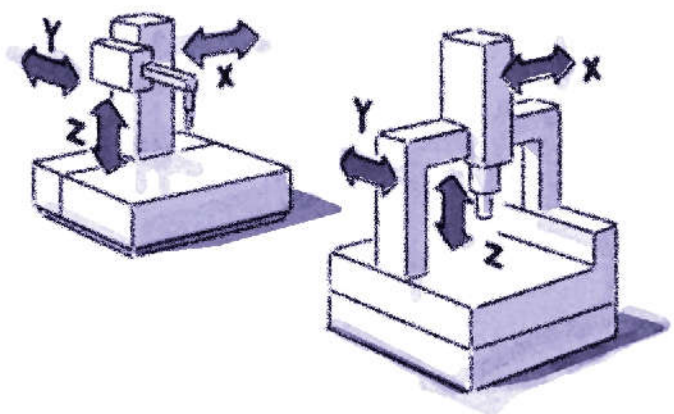
From scribing to form measurement – different types of CMMs



This chapter will give you an overview of different CMM types and their ranges of application.

Having read the following text, you should be familiar with the basic subassemblies and their functions.

Classification of CMMs



A variety of different CMM types have emerged which vary with respect to their field of application, measuring range and accuracy requirement. However, the components responsible for the basic function are identical in all CMM types.

How is a CMM designed?

A coordinate measuring machine has a design similar to that of a machine tool: It has arms or bridges which can travel along three axes located at right angles to each other. These three axes thus form a perpendicular coordinate system. (See also *"Coordinate systems" on page 4_42**.)*

The arms are manually or motor driven and have a separate **length measuring system** *for each axis.*

?Probe head

The probe head probes the workpiece with the inserted probe and reports contact via an electrical signal.

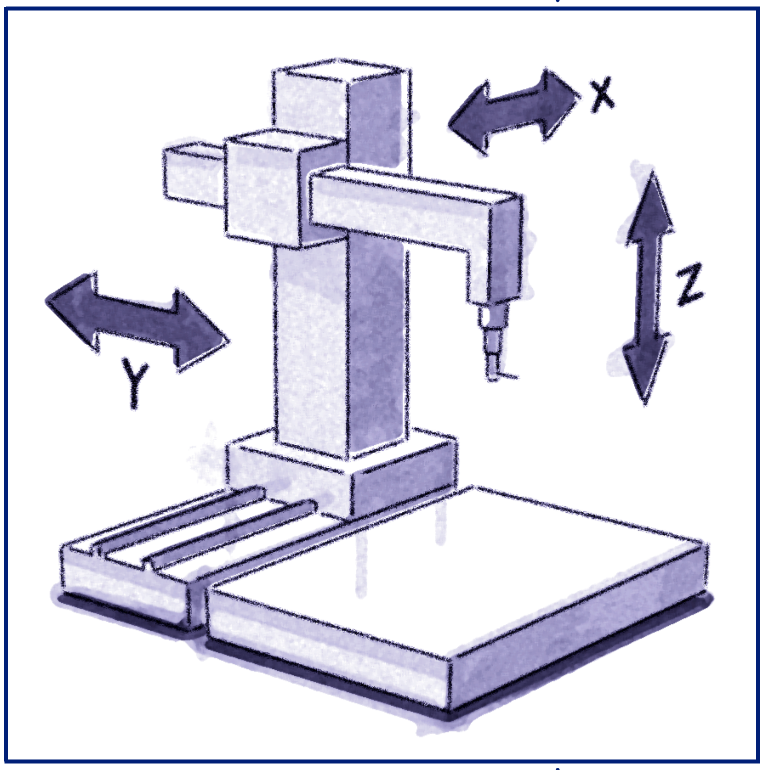
However, in contrast to a machine tool, a coordinate measuring machine has a **probe head** *in which a probe is inserted instead of a tool. Theoretically speaking, this component can reach every point in the CMM s measuring range. The location of the probe is determined when it contacts the workpiece during a probing.*

This information is sent to the internal **control** *in the form of electrical pulses or (in manually controlled CMMs) forwarded directly to the control console. The control processes the received signals and regulates the travel motors.*

The operator controls the CMM via the **control console** *and receives his measuring results in the form of display, screen and/or printer outputs.*

High-end CMM systems also include a **computer** *with the appropriate software (e.g. CALYPSO). This improves the system s operating convenience and provides more information on the status and the acquired or even already evaluated results of measurements.*

CMM types can thus already be classified based on their components. CMMs come in a wide variety of models ranging from basic, manually controlled machines to sophisticated CMM systems equipped with computers and complex software.



What makes or designs are available?

Depending on their design and how the arms are fastened to each other in the three axes, coordinate measuring machines can generally be divided into three basic classifications:

- Bridge-type CMMs
- Horizontal-arm CMMs
- Gantry-type CMMs

Another distinctive feature is whether a trigger or a measuring probe head is used. A measuring probe head features a higher measuring accuracy and enables dynamic probing or scanning.

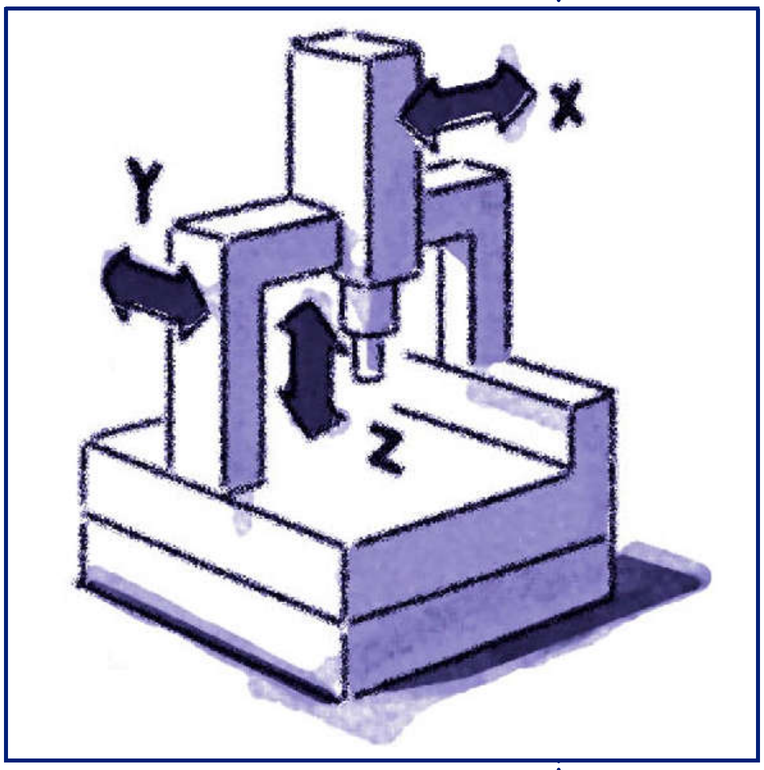
What types are available?

Most coordinate measuring machines are designed to determine the dimensions, and therefore the form and position accuracy, of workpieces.

Special types of machines also based on the fundamental principle of coordinate measurement have been developed for specific types of workpiece inspection (forms, contours, surface finish).

Furthermore, there are also machines which not only can measure, but are also capable of scribing workpieces using suitable auxiliary equipment.

Bridge-type CMMs



Bridge-type CMMs usually comprise a moving bridge mounted on a fixed table. In contrast to designs with a fixed bridge and a moving table, this arrangement enables a very compact construction with heavy permissible table loads and large clamping surfaces.

Attached to the bridge is a vertically moving hollow arm which houses the probe head: the quill. The quill travels crosswise along the length of the bridge and moves the inserted probe head up and down. In this way, the probe head can travel to and probe any point located inside of the measuring volume.

The illustration on the left is only a basic schematic. You may also encounter a variety of designs differing from this one.

Based on the location of the drive, a distinction can be made between two different subclassifications of bridge-type CMMs.

?Measuring volume

In coordinate metrology, the limited space containing all possible measuring points, i.e. all of the points which the probe tip can reach.

Bridge-type CMM with lateral drive

The lateral Y-axis drive of this CMM makes it accessible from all sides. The entire measuring range in the bridge-travel or Y axis can thus be utilized. In addition, pallets bearing workpieces can be automatically loaded and unloaded in this axis.

Lateral-drive CMMs are machines with average to high accuracy which, due to their versatility, cover a wide range of applications in 3D metrology.

They can be equipped either with a trigger or with a measuring probe head (see "Trigger probe heads (ST)" on page 3_28 and "Measuring probe heads and scanning" on page 3_30).

Bridge-type CMM with center drive

The bridge of center-drive CMMs is driven near the machine s center of gravity. This makes it possible to achieve better dynamic rigidity for maximum measuring accuracy and high measuring speeds.

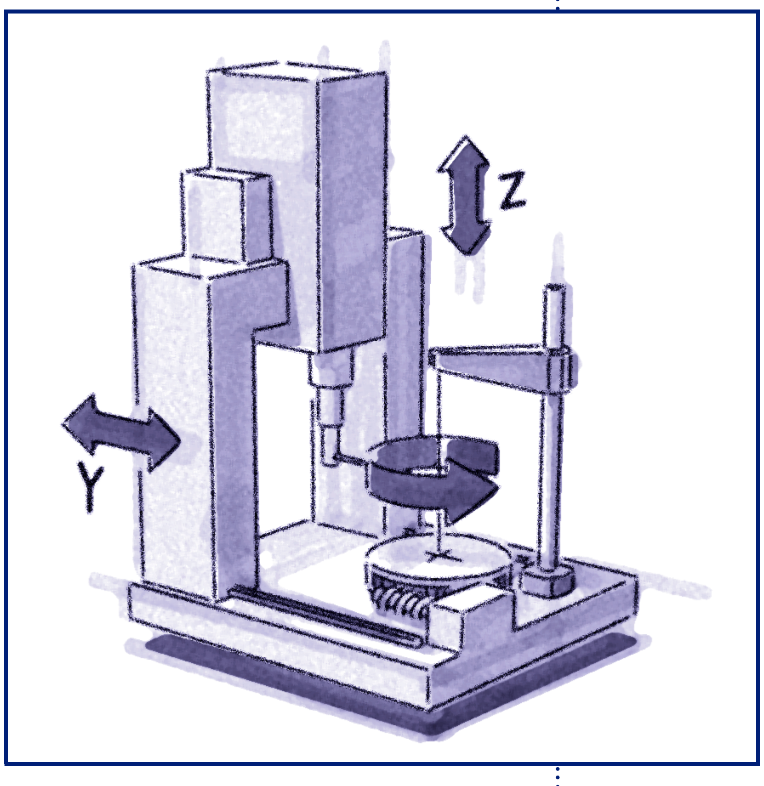
Center-drive CMMs are used wherever maximum precision is required, e.g. in R&D and Quality Assurance Departments. They also can be equipped either with a trigger or with a measuring probe head.

The following table compares CMMs which have a measuring probe head with CMMs featuring a trigger probe head.

Bridge-type CMMs with measuring and trigger probe head

Probe head	Measuring	Trigger
Speed of measurement takeover (single points)	Average	High
Point rate (points taken over per unit of time)	- Single points: average - Scanning: Extremely high	High
Accuracy	Very high	Relatively high
Measurement readout	– At defined measuring force for single-point measurement – During travel for scanning	At minimum measuring force (< 0.1 N)
CMM (examples)	UPMC, Prismo VAST	Eclipse, Vista

Coordinate measuring machines with a rotary table



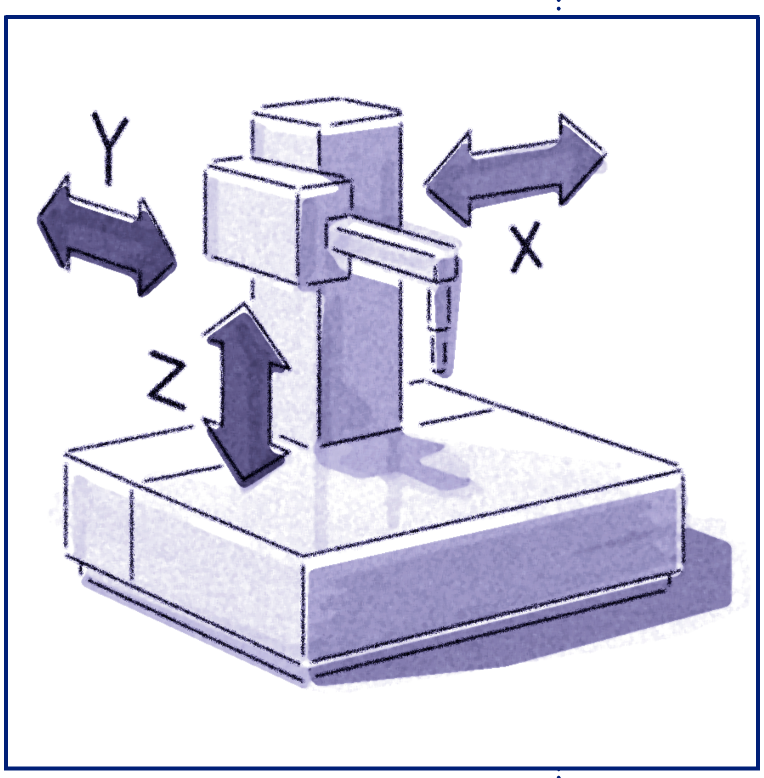
An optional rotary table mounted on the measuring table of the CMM simplifies the measurement and inspection of rotationally symmetrical parts such as gear wheels, rotors and camshafts considerably.

Under ideal circumstances, the workpiece is fastened to such a rotary table and rotated in exactly defined angular steps. The rotary table includes an angle measuring system and a precision driving motor.

The use of a rotary table makes it much easier to probe and compare rotationally symmetric contours. Precise rotation is not required of the probe head, since this function is performed by the rotary table. This means that measuring points which otherwise would be relatively difficult to access can be reached with a basic probe head control.

The rotary table has its own separate coordinate system a polar coordinate system aligned on the rotational axis (see *"Mathematical alignment" on page 5_64**). It is fortunate that the coordinate systems are converted by the computer, since this task is by no means simple.*

Horizontal-arm CMMs



Just as the bridge and quill (the vertical arm with the probe receptacle) are the most conspicuous components of bridge-type CMMs, so the transverse moving or horizontal arm constitutes the main distinguishing feature of horizontal-arm CMMs. The horizontal arm is fastened to a column along which it travels vertically. For this reason, it is also sometimes called a column-type CMM.

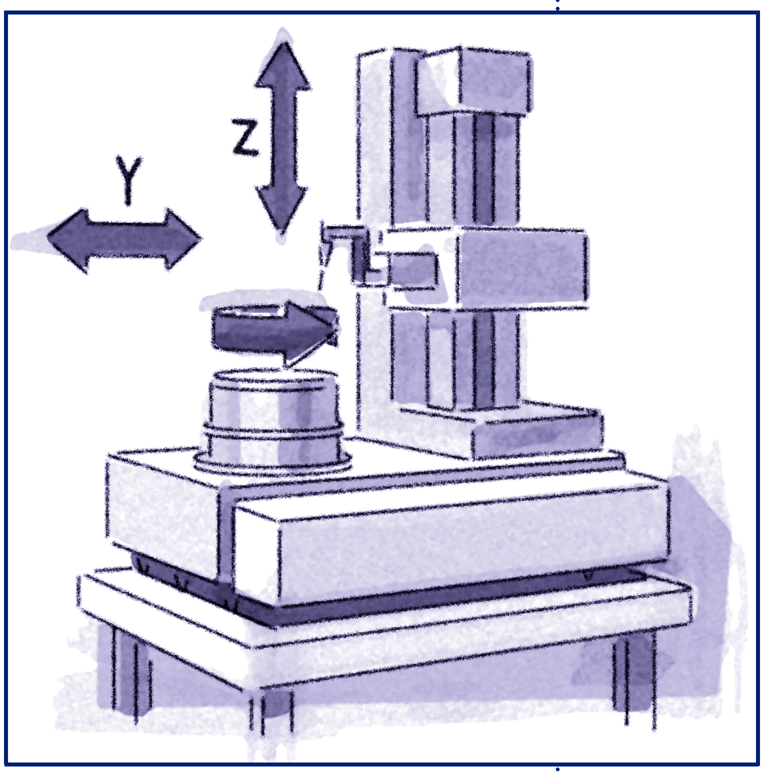
The column itself can be moved back-and-forth.

The column-type design of these CMMs gives them a large measuring range and enhanced accessibility. As a result, larger objects of which e.g. only certain parts are to be probed can be brought into the working area of the CMM. These may include e.g. large-area workpieces like those often encountered in automotive body and engine manufacture.

The accuracy attainable by the machines depends on the given version of column and horizontal arm they are equipped with.

Trigger (see "Trigger probe heads (ST)" on page 3_28), measuring (see "Measuring probe heads and scanning" on page 3_30)or position-independent (RST) probe heads can be used. Some types of CMMs also use DSE probe heads with optical probing systems (noncontact laser probing technique).

Form, contour and surface texture measuring instruments



An entire group of coordinate measuring machines is specially equipped for checking specific surface qualities of workpieces.

These may be either geometric qualities (shapes, curves) or machining qualities (roughness).

The general design of these instruments as well as the type of probes and software they use enable them to perform their special measuring jobs faster and more conveniently for the user.

In most cases, the measuring range is encapsulated and special probes and probe configurations are used.

This group of coordinate measuring machines has been mentioned here for the sake of completeness, however, will not be further dealt with in the following text.

What you should know now

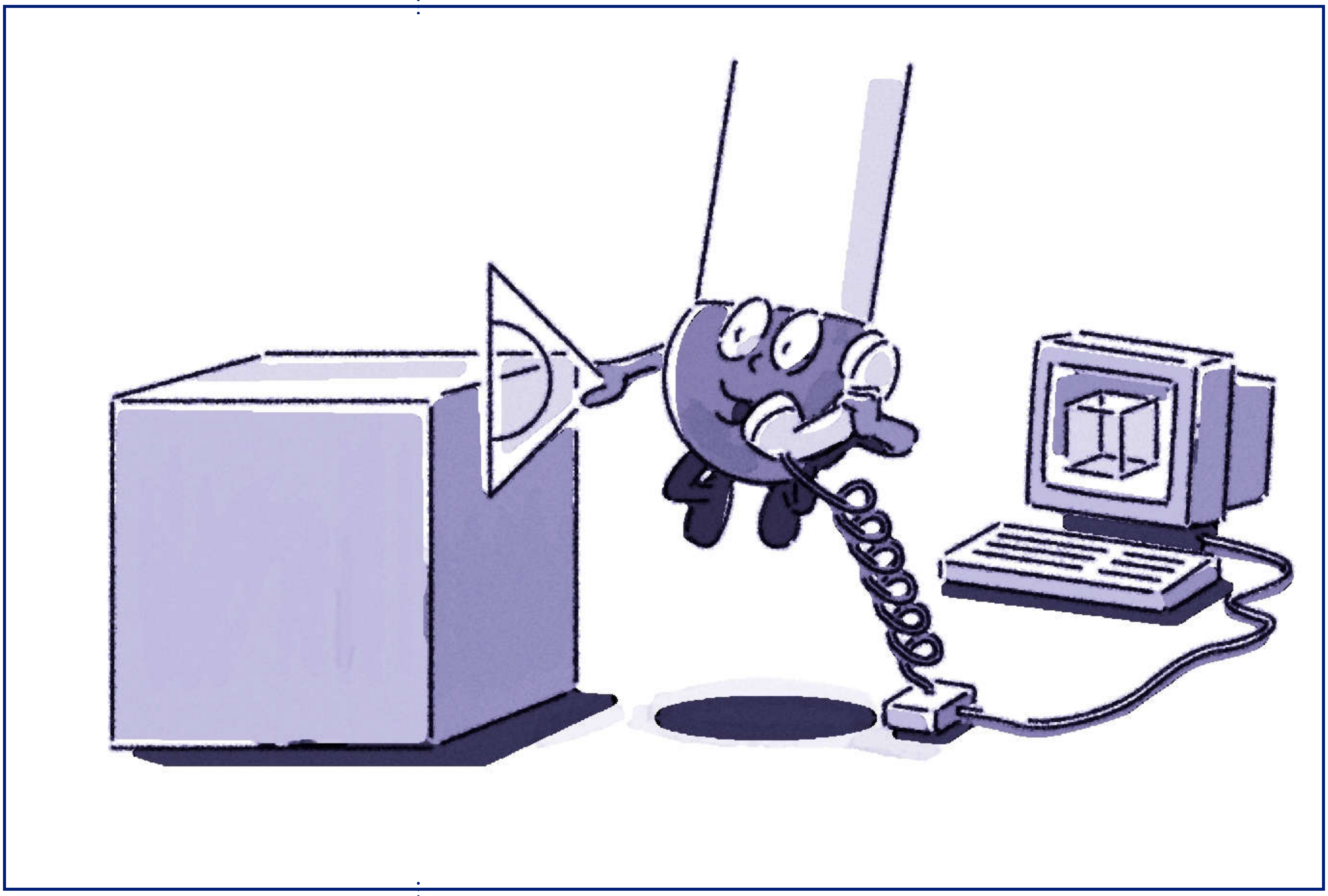
What purposes are coordinate measuring machines used for?

Name the different types of coordinate measuring machines:

What are the components of a coordinate measuring machine?

3

From probe tip to program – path of the measured value



Now let's move on to the interesting part! In this chapter, we'll trace the path of the measured value from its acquisition to the point where it finally reaches your computer.

What's more, you'll be introduced to terms such as length measuring system and closed loop and find out the most important facts about probes and mechanical probe heads.

Path of the measured value

Imagine being in a room full of objects you can not see e.g. due to a power failure. For t his reason you grope ahead with outstretched arms. Suddenly your index finger touches something. What happens then? A "contact" signal moves from your finger to your brain, which then sends a "stop" signal back to your finger. Based on the position of your arm and fingers, your brain now knows where the object you contacted is located.

A CMM works similarly. Here as in our example, numerous components contribute to the generation of a measuring result.

Probe head

The probe head reports contact with the workpiece in the form of an electric signal.

Probing on a workpiece

The **probe head** is moved toward the workpiece via manual or CNC control. A probe consisting of one or more styli with **probe tips or spheres** attached to their ends is fastened to the probe head. As soon as the probe tip contacts the workpiece, the control is informed accordingly.

Probe tip

The probe tip used for probing is a high-precision sphere made of ruby, which is an extremely hard and relatively nonmalleable semiprecious stone.

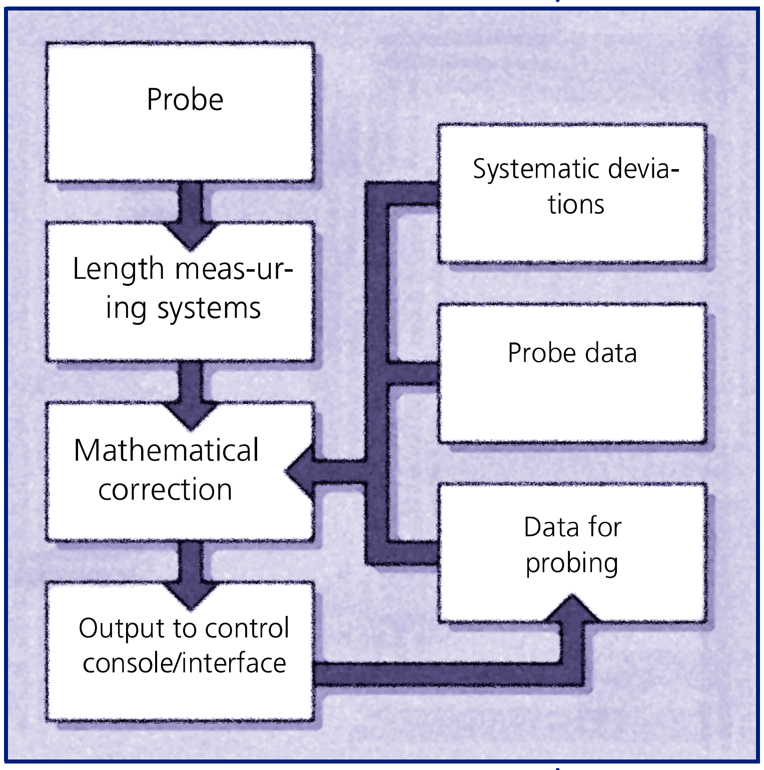
Coordinates for control

Then the data measured are continuously read off from the three **length measuring systems**. The control determines the position of the CMM at this point of time.

If a measuring probe head (see *"Measuring probe heads and scanning" on page 3_30*) is used, its internal length measuring systems will also output certain other correction variables during a dynamic measurement. This data will also be processed by the control.

Length measuring system

A length measuring system outputs the distance between two points in the form of electric signals.



Corrections in the computer

The computer then calculates all known *systematic CMM deviations* into the coordinates.

The value determined undergoes further correction runs since other circumstances and influences also must be considered e.g.:

- the *direction of travel* during probing
- the *inclination* of the probed surface
- the used *probe* used.

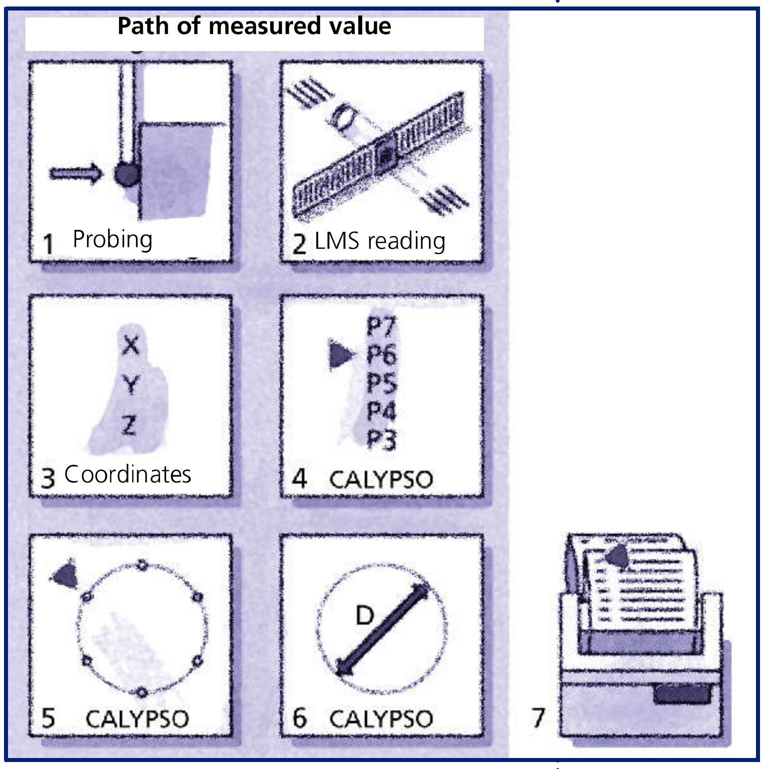
The probing location is thus determined and calculated with maximum precision.

Coordinate output and evaluation

The coordinate values are output to an evaluation program (e.g. CALYPSO). In most cases the desired result is not the probing location itself, but rather, one which has either been derived from or calculated based on this value.

What does this mean? The desired result may be e.g. a location not directly measurable such as the center point of a circle, a geometric variable like the slope of an axis, or another quality criterion which has not yet been calculated.

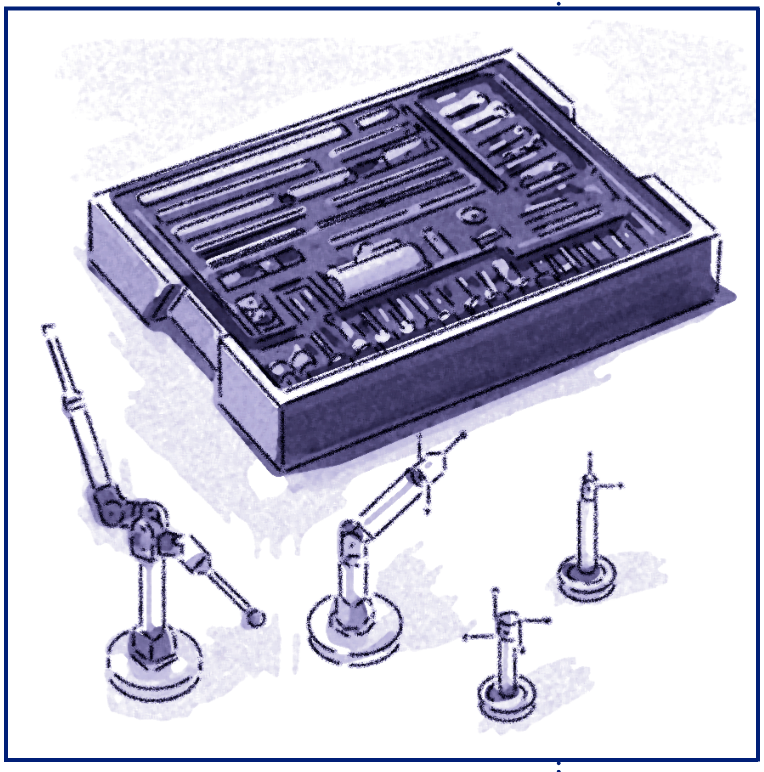
Path of measured value with CALYPSO



The illustration on the left shows the individual steps from probing to output when working with CALYPSO software.

1 Probing
2 Readout from length measuring system (LMS)
3 Determination of (corrected) coordinate values
4 Reading as point of a measured element (circle) in CALYPSO
5 Calculation of measured element (if necessary, with calculation of best-fit substitute element)
6 Determination of inspection characteristic (diameter)
7 Output (e.g. to printer)

Probe heads, styli and probe accessories



The heart of the coordinate measuring machine is the probe head with its components. The following text deals only with probe heads using probes which mechanically contact the workpiece. These can be further classified into two groups: trigger and measuring probe heads (see below).

Mounted on the probe head is a removable probe containing one or more styli, each of which has a probe tip at its free end. These probe tips are made of ruby, a valuable, red semiprecious stone, to minimize their deformation and wear.

Note on terminology: A probe is sometimes also called a probe configuration if it has been assembled from multiple styli.

Selecting styli

The CMM model and the possibilities it offers chiefly determine which styli *can* be used. On the other hand, the styli you *require* depend on the workpiece and measuring job at hand.

For example, you require longer styli for deeper bores. For this reason, many CMMs come with "probe kits" containing components which can be used to assemble the probes you need for your measuring work.

Probe change

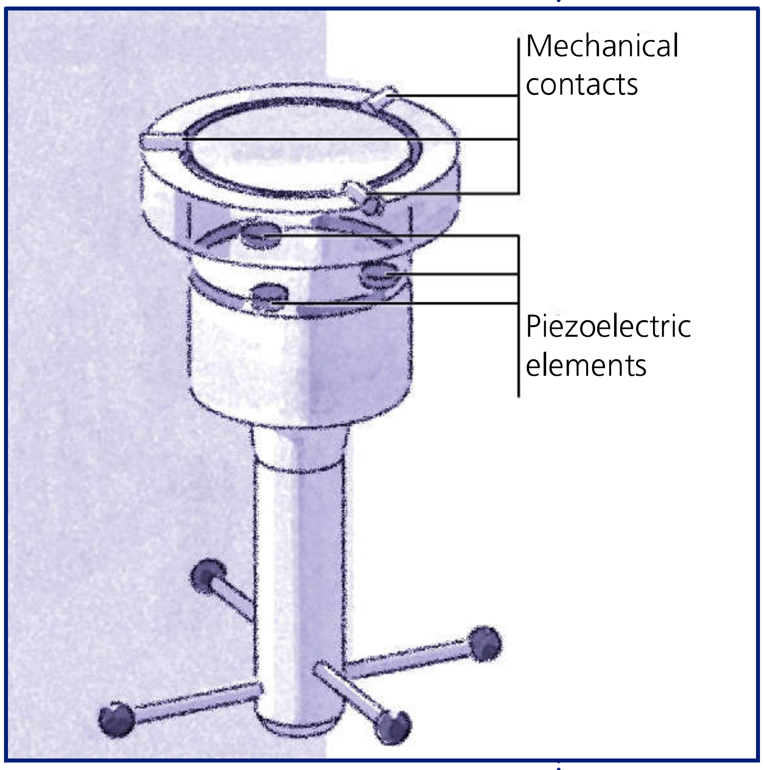
It used to be necessary for the operator to define the position of and calibrate each probe (see *"Probe calibration" on page 5_60*), following every probe change. However, today almost all CMMs are equipped with clamping and plugging devices of such high precision that this is no longer necessary.

As a result, it is now possible to insert the currently required probe during routine operation and use it without delay.

Probe magazine

If the CMM is equipped with a probe storage magazine or rack, it can function so to speak "as its own robot" by removing the probe (requested by the software or the operator) from the magazine and then redepositing it there when it is no longer required.

Trigger probe heads (ST)

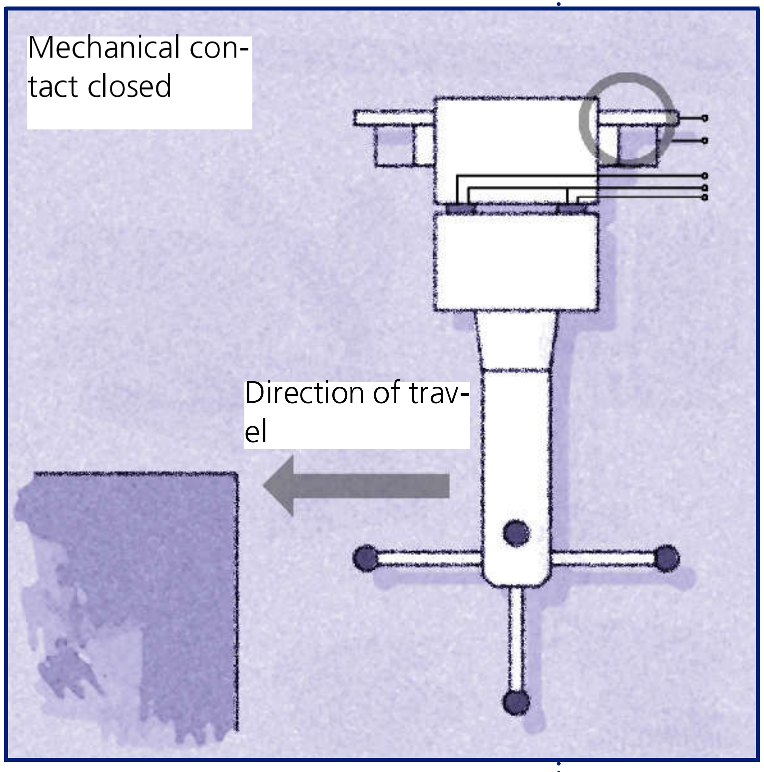


The moving part of the "trigger" probe head is connected to the housing via a buckling mechanism (a three-point bearing with **piezoelectric contacts**).

This buckling mechanism is designed as a prestressed three-point bearing which protects the probe and probe extension against damage following contact with the workpiece. The resilience of the buckling mechanism can be adapted to the weight of the probe by adjusting a rotary ring. The permissible probe weight depends on the CMM type.

? Piezoelectric element

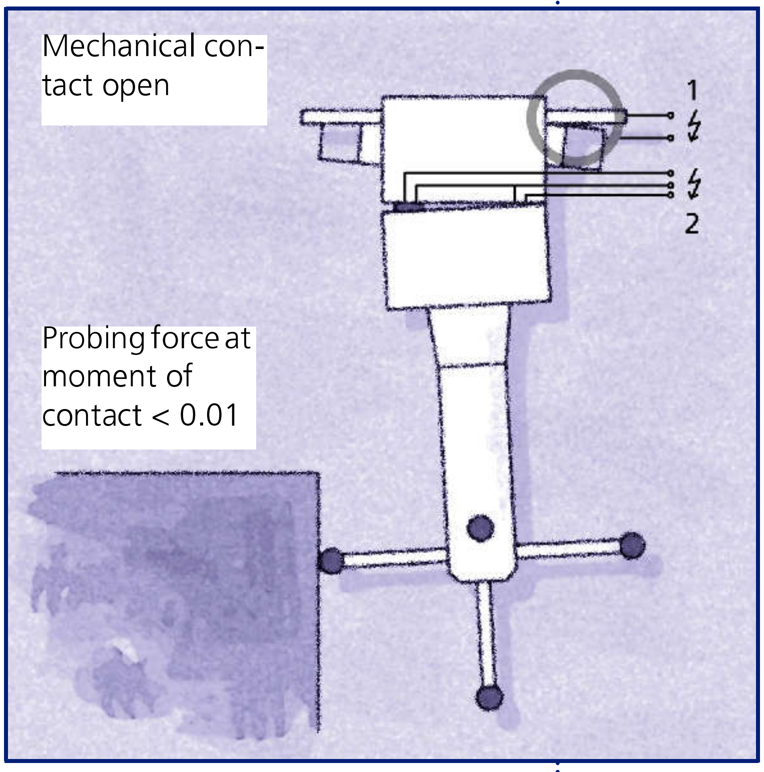
Certain materials generate an electric voltage in response to mechanical pressure.



How the trigger probe head functions

The probe head moves toward the workpiece at probing speed.

When a certain probing force acts on the piezoelectric measuring elements, this triggers an electric pulse which then starts the readout of the path measuring systems. These readout values are not directly input to the computer, but only buffer-stored!



If the mechanical contact opens within a preset period of time (depending on the machine type) after the probe was deflected by a minute angle on contacting the workpiece, the travel motors (of motor-driven CMMs) will stop and the computer will input the measured value.

Position-independent trigger probe head (RST)

In principle the RST is a miniature version of the trigger probe head (ST). Its maximum probe weight is so negligible that no (weight-related) probe balancing is required.

Due to its lightweight probe, this probe system can also be used on CMMs with very high acceleration values and under extremely adverse ambient conditions.

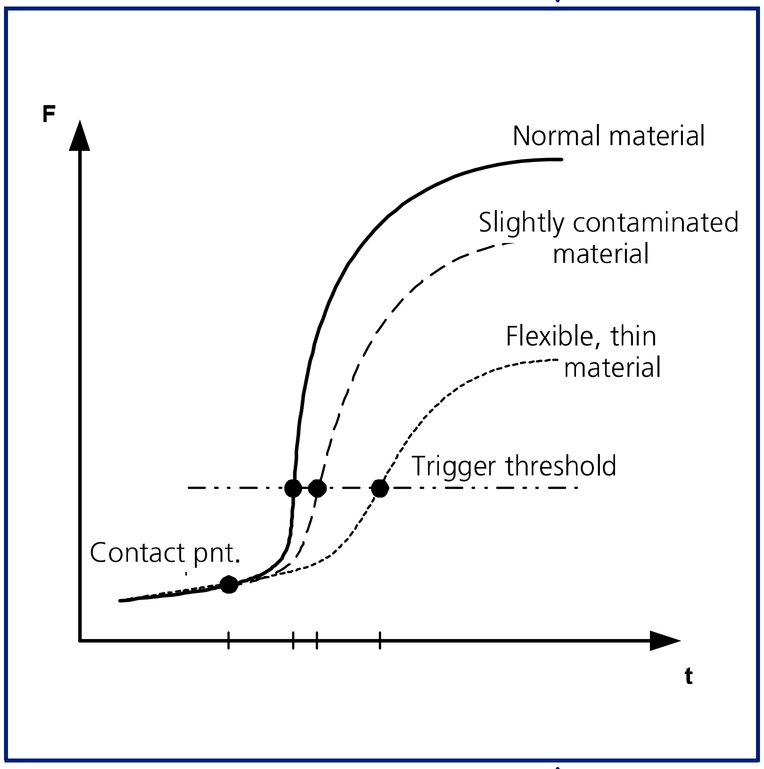
In connection with long extensions, the RST is especially suitable for deep immersion into and measurement of hard-to-access locations, e.g. in car body subassemblies.

? ATAC

Adaptive Touch Advanced Control

Trigger probe heads with ATAC

The piezoelectric elements of a trigger probe head react differently to various workpieces: the hardness of the material, its surface finish and any possible oil contamination result in varying signal characteristic curves. The size of the probe stylus may also play a role.

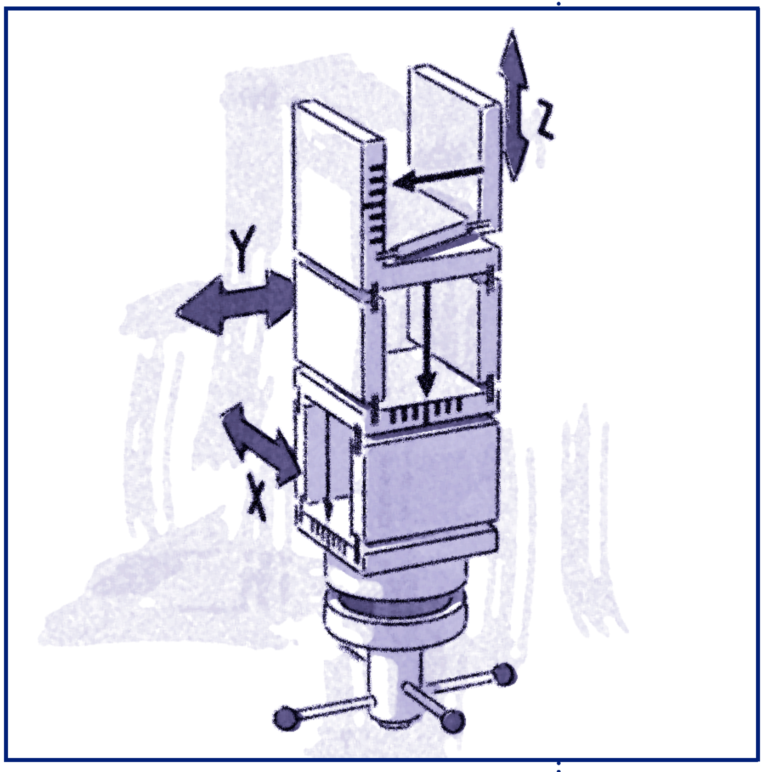


The force-time characteristic of the piezoelectric signal is recorded and analyzed "online" by an extremely fast probe head electronics unit. The exact contact point is then calculated from this value.

In this way, even the most difficult probing conditions can be dealt with reliably, repeatably and much more accurately than ever before. The measurable workpiece spectrum has been extended; fewer probing repetitions are required.

A certain workpiece finish or surface quality is usually assumed. However, if a trigger probe head is equipped with **ATAC**, the CMM can analyze the workpiece material based on the behavior of the probe head, and therefore of the material. This information is then taken into account when determining the probing point.

Measuring probe heads and scanning



The measuring probe head has a higher accuracy and enables the **scanning** of surfaces.

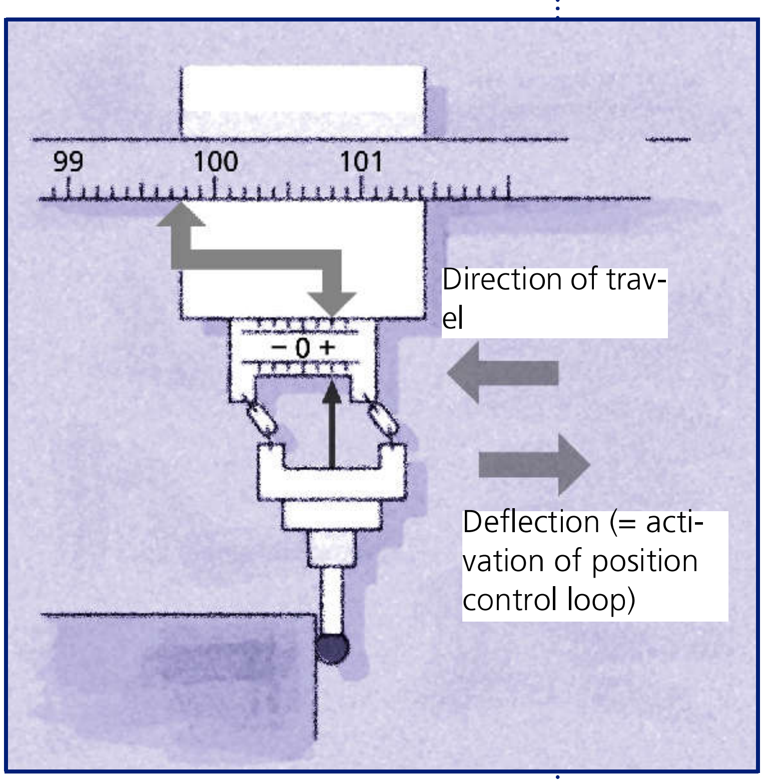
Design of the measuring probe head

A measuring probe head contains three parallelogram springs, one for each of the three axes, i.e. X, Y and Z. These (usually stacked) parallelogram springs make it possible to parallel-adjust the probe pick-up by very small amounts (e.g. ± 2.5 mm) in each axis. Each individual travel axis has its own integrated length measuring system; hence the name "measuring probe head".

The probe head can adjust itself in all three axes via the corresponding parallelogram springs. Each of the parallelogram springs can also be individually "clamped" or locked to prevent further or unwanted adjustment in the corresponding axis.

? Scanning

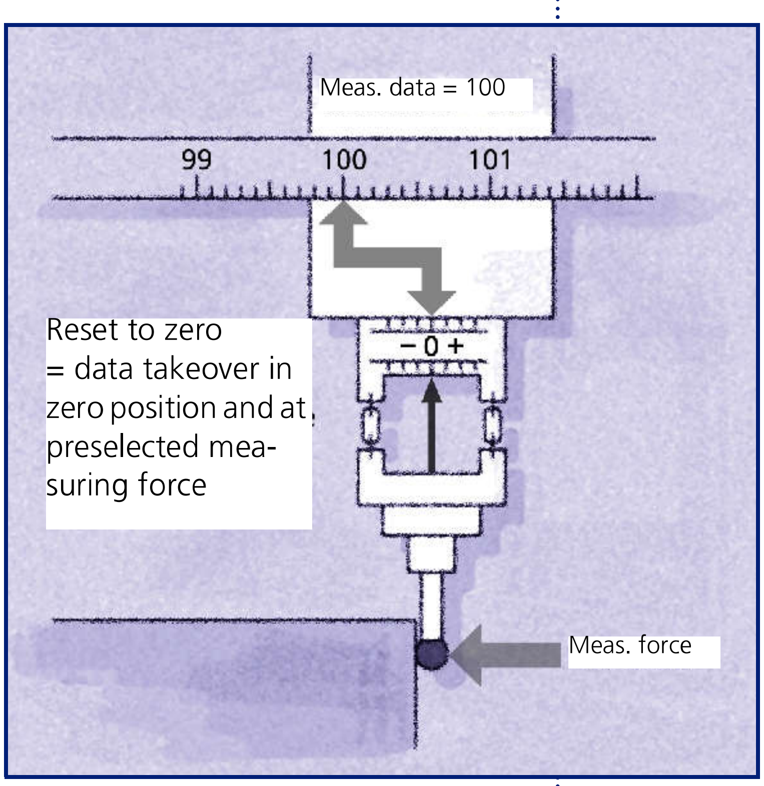
In coordinate metrology scanning generally refers to continuous probing of contours with dynamic measurement take-over, resulting in a dense point sequence.



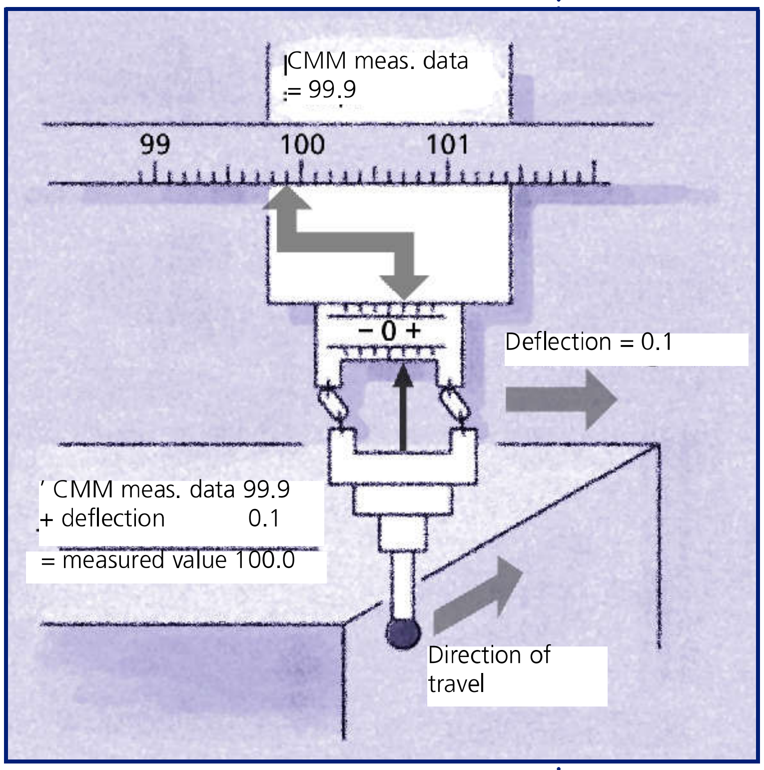
How static measurement works

Static measurement is the measurement of individual points. The probe or stylus first travels to the workpiece. Then, on probing the workpiece, it is pushed slightly away from the probe head pick-up against the probing direction.

A probing status is recognized as soon as this probe deflection exceeds a specified amount. Then the system is switched from the **position control loop** to the probing control loop and the CMM carriage moves back until the length measuring system in the probe head has reached its zero (home) position at a preselected **measuring force**.



Then the measured values are read out by the path measuring systems and transferred to the control in coordinate form.



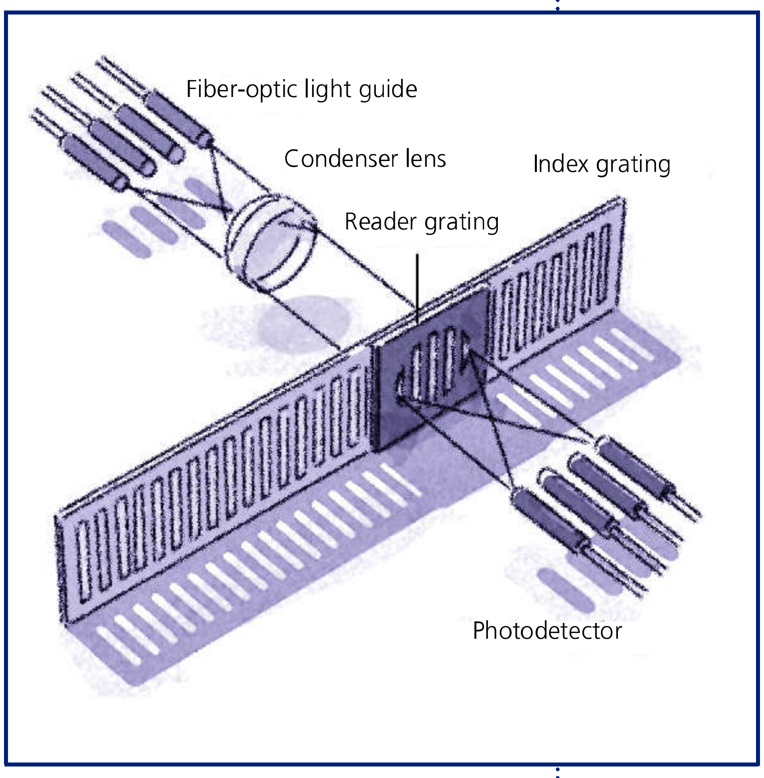
How dynamic measurement works

Dynamic measurement is a **scanning** mode which is possible only with a measuring probe head. In this mode of measurement, the measured values are taken over or transferred with the probe head in the deflected state. For this reason, dynamic measurement is faster than static measurement.

How is this made possible? Parallel deflection of the probe generates a value in the CMM length measuring system which deviates slightly from the actual value. And exactly this deviation is measured by the probe head length measuring systems! The measurement is generated by simultaneously reading out the value of the CMM and the probe head measuring systems and figuring both of them into the calculation.

Scanning is performed by "dragging" the probe stylus along the surface of the workpiece. This technique makes it possible to acquire considerably more probing points in a shorter period of time to facilitate the measurement and evaluation of curvilinear surfaces, gear wheels or profiles.

Length measuring system and closed loop



Length measuring system

A separate length measuring system is integrated in each axis. This enables the CMM to "know" where the probe head is located at any given moment. The values measured by the length measuring systems are continuously transmitted to the computer during probe head travel.

The different designs and types of systems used vary considerably and will not be described here at length. One important point should, however be noted: the variety most commonly used are **incremental systems** with a graduated grating as their material measure or standard of measurement.

The illustration on the left shows a photoelectronic incremental system: a smaller, illuminated reader grating or reader head is moved along the index grating or scale by the travel movements of the probe head. This causes the grating gaps to open and close, thus generating light signals which are then converted to electric signals. Finally, these signals are evaluated and converted to a dimension equaling the distance traveled by the CMM carriage.

? Incremental system

Incremental systems take into account the increase or "increment" and the decrease occurring during travel to calculate the instantaneous length. I.e. only the difference in reference to the previous reading is measured.

Angular-position measuring system

A rotary table also has a measuring system to measure its rotation (see *"Coordinate measuring machines with a rotary table" on page 2_19*). Since its fixed scale revolves in a circle around the rotary table, the measured *length increment* is equal to the *angular increment*.

Automatic control

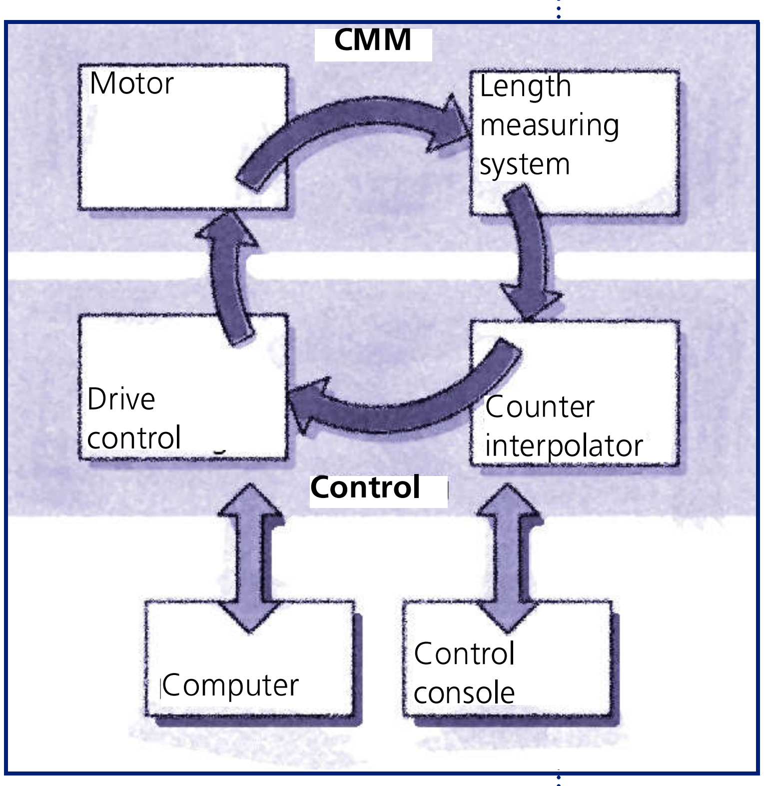
In CMMs with an electronic probe head control, the length measuring systems are also used to move the probe head to the correct location during an automatic measuring run.

The CMM carriage is driven by precision motors in all three axes. In the manual mode, the operator moves the probe head to the desired position by deflecting the joysticks in the desired direction of travel while constantly keeping an eye on the path traveled by the probe head.

However, for automated measuring runs the CMM itself must be able to travel precisely to each desired location. The machine carriage motors can be controlled exactly as required for this purpose.

Closed loop

In a closed loop (control), a measured value is fed back to influence itself in such a way that a preset value is reached or maintained.



Position control loop

Simpler, exacter and more reliable control can be achieved with **closed loop control** than with direct (open-loop) control. The information provided by the CMM's own length measuring systems can be used to move the probe head to the desired location. The control, drive motors and path measuring systems are here combined to form a single *position control loop*.

This functions as follows:

- The program or the operator determines the coordinates of the location to where the probe head should travel.
- The length measuring system in the CMM reports the current position to the computer.
- The computer compares the actual and nominal positions. If the nominal position is not yet reached, the drive control outputs current to the drives until the length measuring systems report that the actual and nominal positions are identical.

When the control informs the computer that the preset nominal value and the actual position agree, the next program step, e.g. probing, is then processed.

What you should know now

What components are involved in determining the probing location?

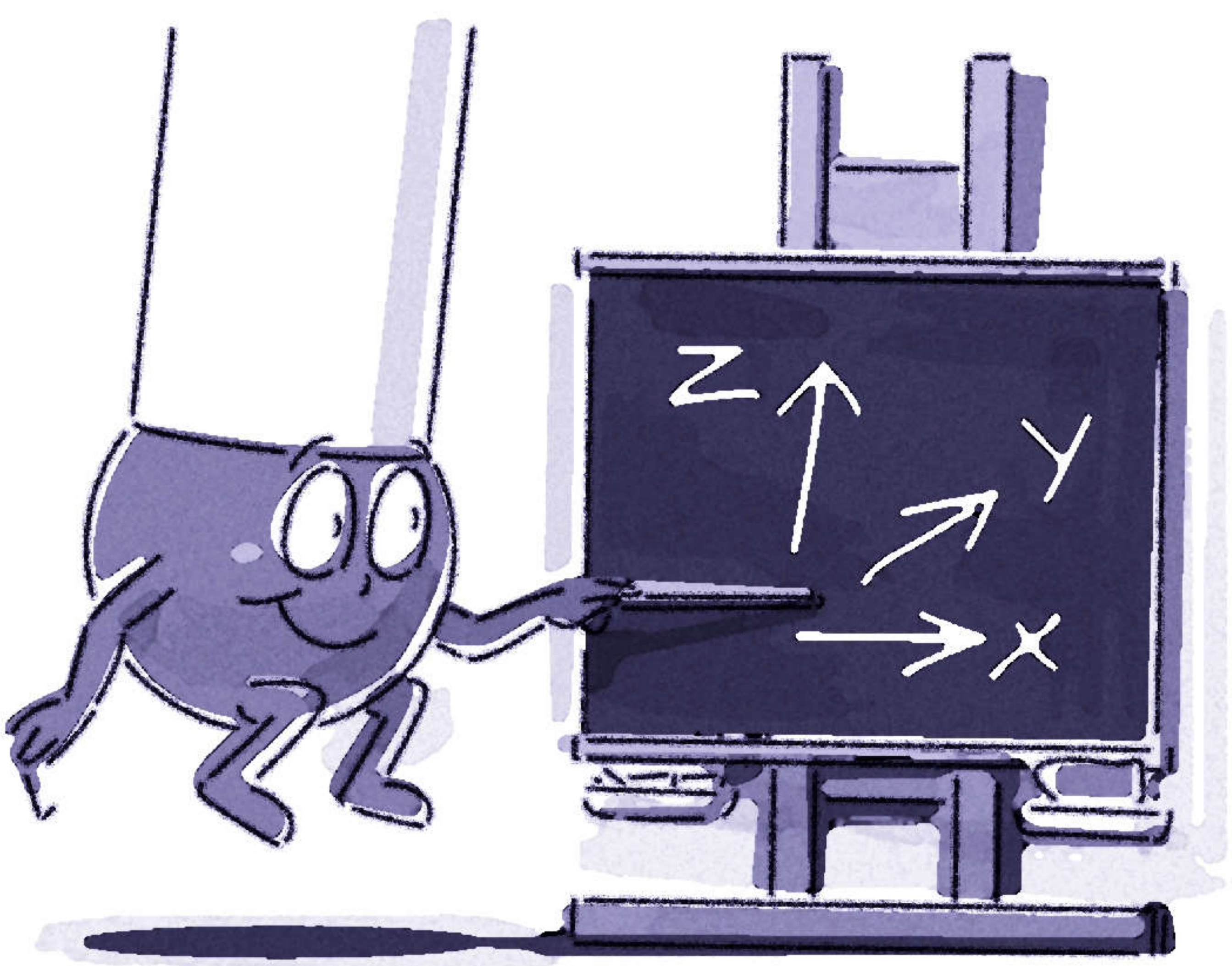
Explain the function of a trigger probe head.

Explain the function of a measuring probe head.

How does scanning work?

4

From vector to projected angle



Basic mathematics ... some of you may get stomach pains at the mere thought of this subject matter.

So, bearing this in mind, we have done our best to explain terms like 'vector' or 'coordinate system' and many statistical terms as clearly and simply as possible.

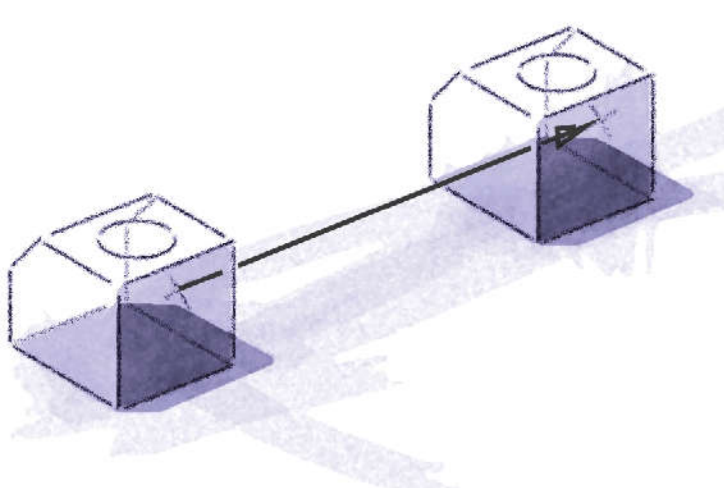
Because we believe that this knowledge will improve your measuring success.

After all, such measurements can not be performed completely without math: e.g. you will repeatedly be involved with projected angles.

Vectors and normals

?Vector

A vector is defined by a direction and an amount (length).



Vector symbolizing a three-dimensional linear movement

Everyone knows what numbers are: they can be used to specify lengths, sizes or quantities (e.g. three apples, a wheel base of 2.45 m, an apartment with 87 sq. m floor area).

All of these figures specify one-dimensional objects: this means that all possible lengths or sizes can be arranged along a single line (a one-dimensional object). And for two randomly selected numbers you can always determine which of them is greater, i.e. their proper arrangement on the number scale.

And since numbers can be arranged on a scale, they are also sometimes referred to as *scalar quantities*.

Vectors

However, numbers alone are not always sufficient to clearly define all functions. For example, if you want to describe the three-dimensional movements of a robot, one-dimensional numbers alone simply won't do.

Vectors are used to demonstrate the direction and length of a movement. You might try imagining a vector as the displacement of a point in a specific direction and by a specific length. And that's the reason why vectors are often drawn as arrows.

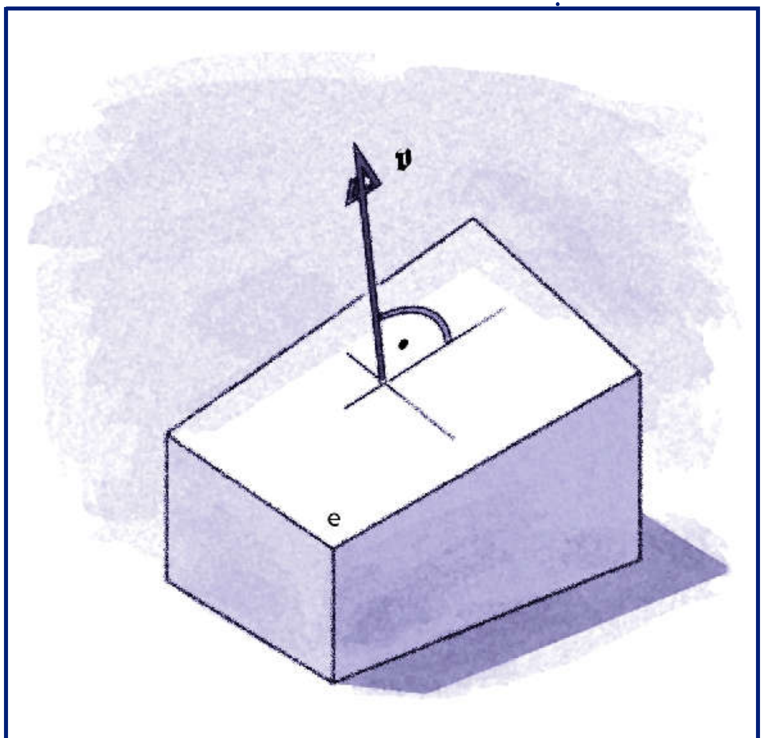
Vectors can be added to each other or multiplied by a number. This corresponds to the performance of different movements in succession or the repeated performance of a single movement. The results of such "operations" are then also vectors.

Normal

Each plane defines exactly one direction perpendicular to its own surface in three-dimensional space. This direction is called the normal.

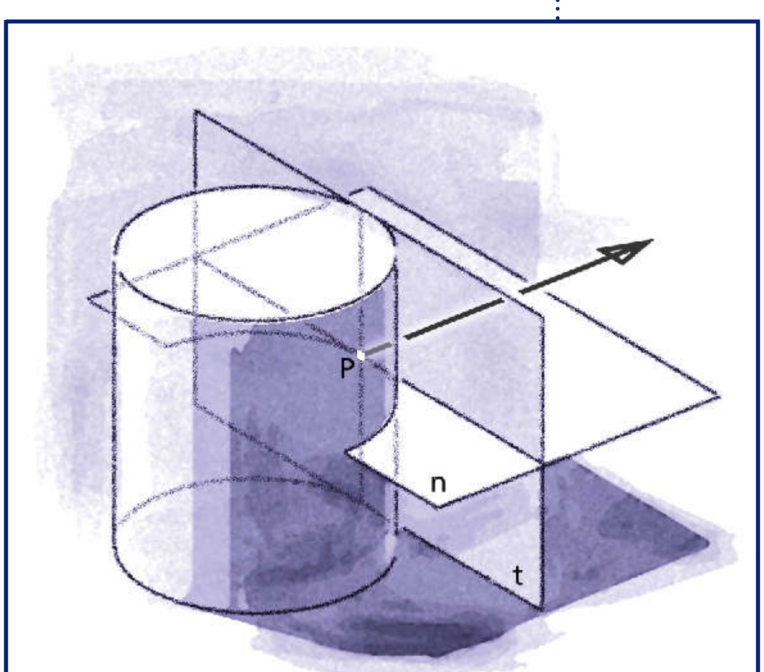
Normal vector

The **normal vector** or, as it is also called, the **normal** is used to characterize the inclination of a plane or a surface "around a given point".



Normal of a plane

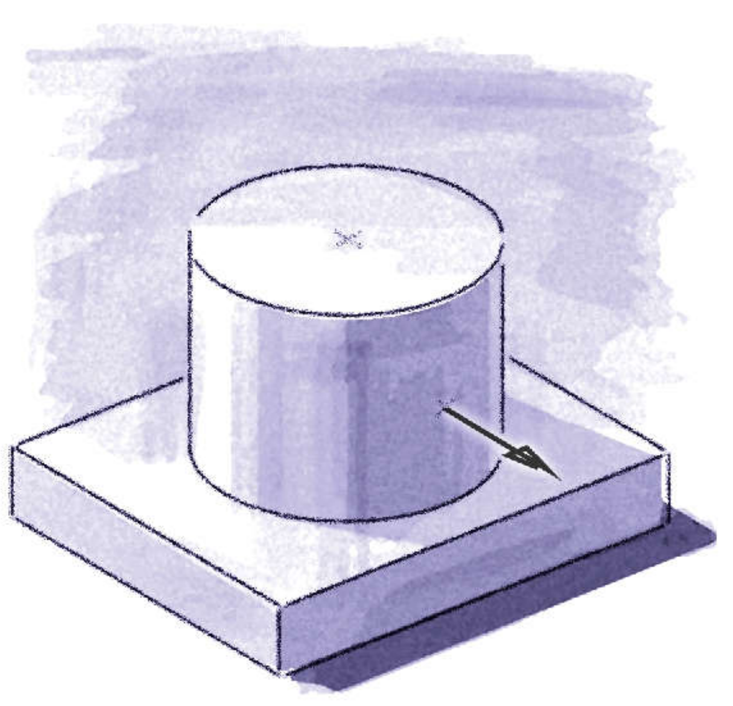
The normal vector of a plane is the vector perpendicular to every random line running through that plane. Only one such direction exists in three-dimensional space. Each plane thus has exactly one normal which remains the same at every point.



Tangential plane of a surface (cylinder)

Normal of a surface at a specified point

A normal can also be defined for a point on a nonplanar (i.e. curvilinear) surface: This is done by simply defining the normal of the tangential plane at the given point. The reason for this is that every point of a surface has only exactly one plane which both passes through that point and conforms to (or coincides with) the surface in every direction: the tangential plane.

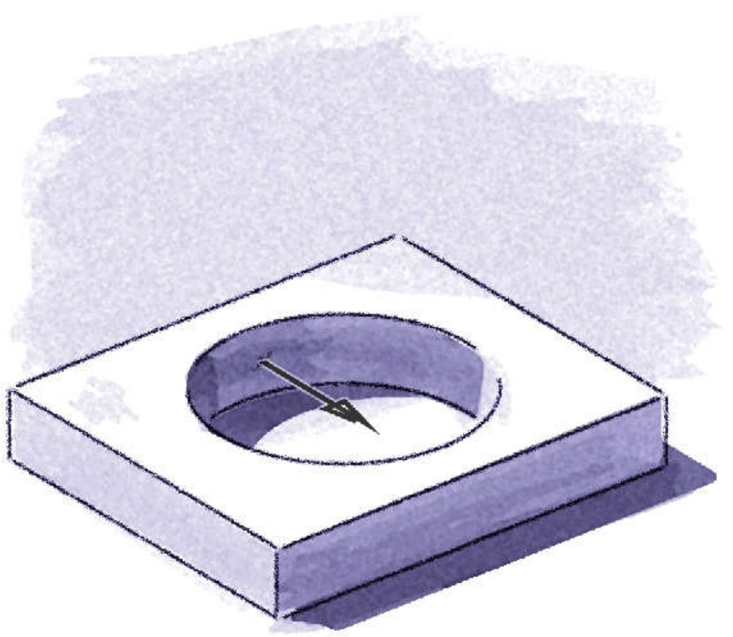


Where does the normal vector point to?

For areas it makes no difference whether the normal points "up" or "down". On the other hand, this point can not be viewed as unimportant in cases involving the surfaces and contours of solid bodies.

The location of a solid body's "inner" or "outer"surface is an important piece of information when performing measurements with automated coordinate measuring machines. After all, a body can only be probed from the outside.

However, the CMM can not see the workpiece the way we do. For this reason, there is a convention stating that the normal must always be specified pointing away from the body (i.e. outward).



The normal vector points to the outside

Example: a cylinder

Thus, for example, a cylindrical surface may represent either the periphery of a cylindrical bore or the outer surface of a peg. In the first case the CMM must probe the cylinder from the inside and, in the other case from the outside.

The surface normal points toward the "inside" of the cylinder (but outward from the workpiece) in the first case and outward from the cylinder in the second case.

Planes, straight lines and points

To understand how measuring elements and geometric terms are used in CALYPSO, you should have a general idea of the relationship between points, straight lines, planes and geometric figures in three-dimensional space.

How are geometric objects defined?

Formulae (e.g. equations) can be used to designate geometric objects, i.e. sets of spatial points. The corresponding geometric object is then equal to the set of all points which satisfy the equation. An example of this is the set of all points which have a distance of 7 cm from point M – i.e. the spherical surface which surrounds point M and has a radius of 7 cm.

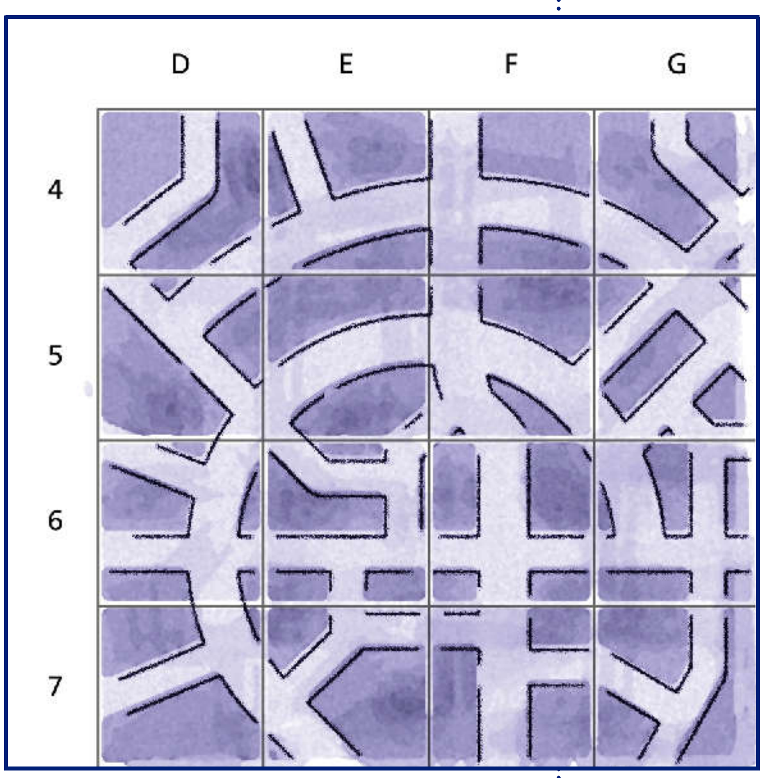
More commonly, however, several points on the geometric object are specified along with the kind of geometric object involved. CALYPSO can automatically recognize what kind of geometric object is involved based on the points measured.

The minimum number of points required to clearly define a geometric object can always be exactly determined based on the laws of mathematics. One point less and the object is indefinite. One point more and the object is generally no longer definite."Generally" here means that the "one point too many" which has been specified may coincidentally belong to the object previously defined, however, this is not necessarily the case.

For example:

- 2 points define a straight line.
- 3 points (not located on a single straight line) define a plane.
- One straight line and one point (not located on the straight line) define a plane.
- 3 points (not located on a single straight line) define a circle.
- 4 points not located in a single plane define a cylinder.
- 4 points not located in a single plane define a spherical surface.

Coordinate systems



The position of spatial points can be specified using a coordinate system. One simple example of how this is done is the coordinate grid on a city map. Let's assume for example that you're looking for Main Street in Anytown USA. The street directory of your city map indicates that Main Street is located in square "F6". You then move your finger from left to right until you find column "F" and from top to bottom until you pinpoint square "F6". That's where Main Street must be located.

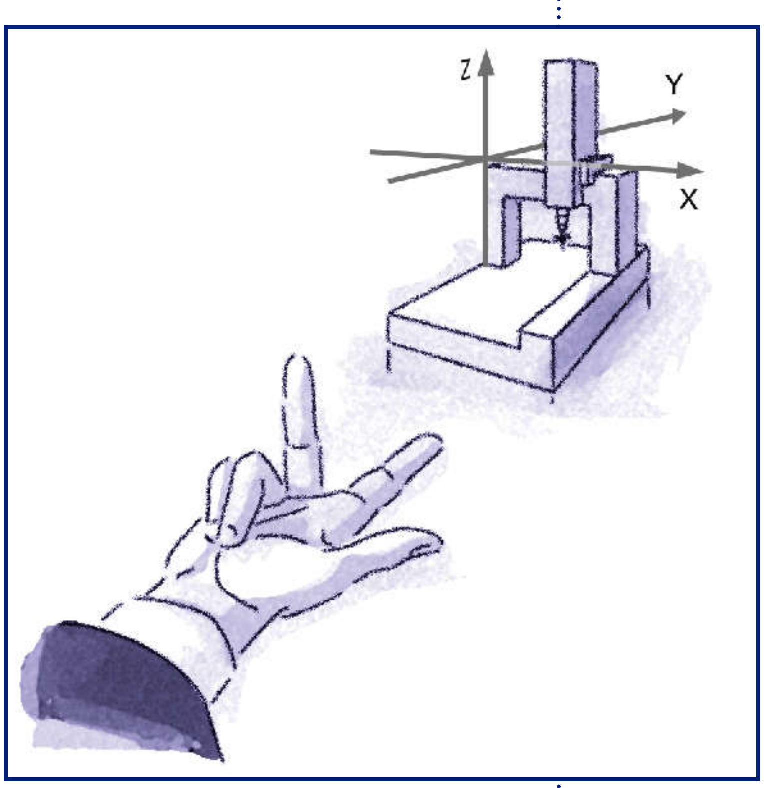
"Right-hand rule"

The relative location of the X, Y and Z axes of a Cartesian system resembles a tripod formed by the thumb, index finger and middle finger of your right hand.

Cartesian coordinate system

The most common form is the rectangular, three-axis Cartesian coordinate system. Three aligned reference axes are here located at right angles to each other at the zero point. These three axes are usually designated as "X, Y and Z".

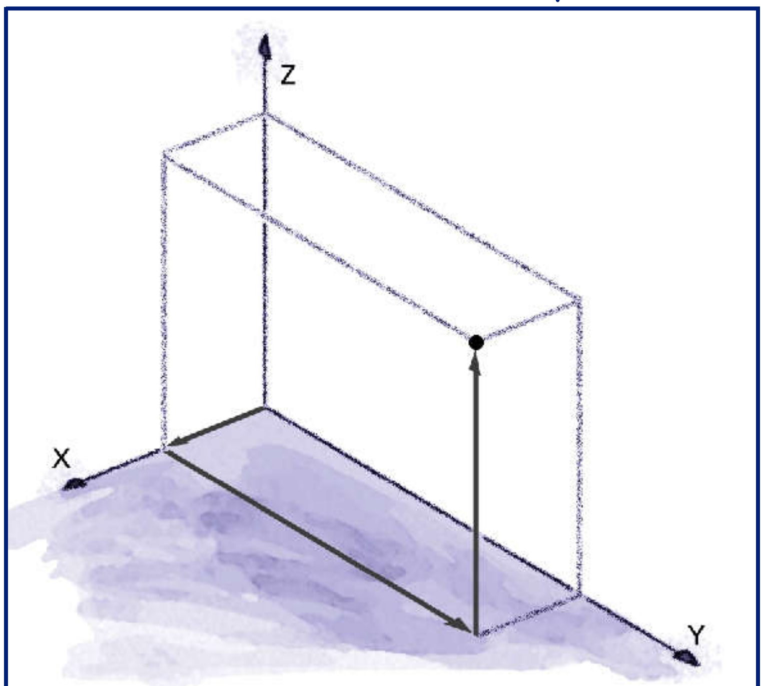
The direction of an axis is usually indicated by an arrowhead. The axes must have a positive orientation, i.e. the relative position of the X, Y and Z axis must be the same as that of the thumb, index finger and middle finger of your right hand (**right-hand rule**).



This rule is important. Without it misunderstandings might occur since, theoretically speaking, the third axis could also point in the opposite direction.

What do the coordinates tell us?

Each spatial point forms a right parallelpiped in connection with the XYZ-axis tripod. The lateral sides of the parallelpiped in the three axes are the coordinates. Like the city map mentioned above, they tell you how far you must go in a given axis to reach the point concerned.



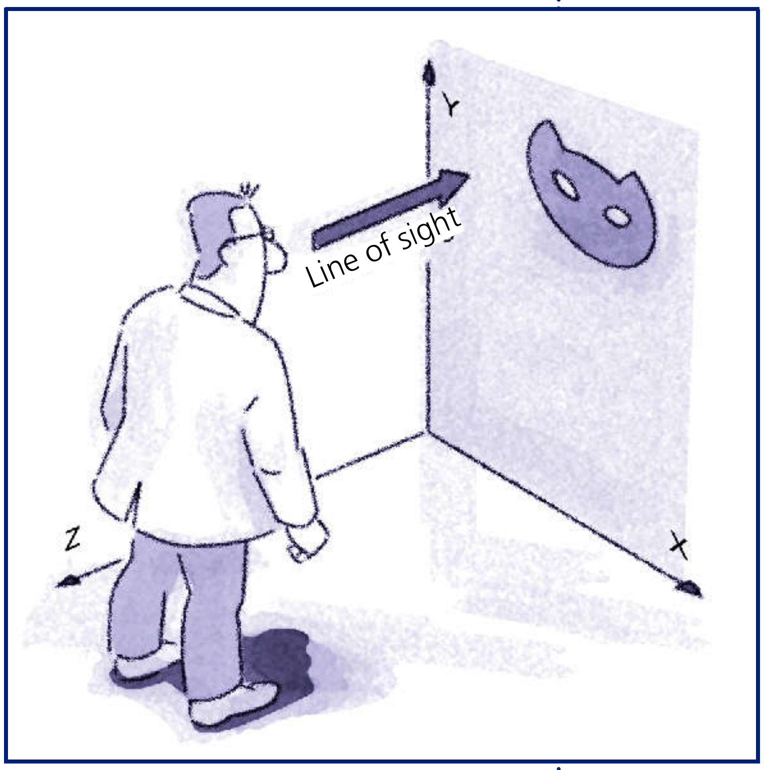
The coordinates lead up to the point

Example: a coordinate measuring machine

On a coordinate measuring machine, the three axes of the machine coordinate system can easily be recognized by the direction in which the probe head is traveling: The transverse carriage travels crosswise in the X axis, the bridge runs back and forth in the Y axis and the quill moves up and down in the Z axis.

The zero point of the machine coordinate system is defined by the manufacturer. It is located at the "top rear left corner" of bridge-type CMMs when viewed from the front. As a result, all coordinates measured except for the X coordinate are negative in machines of this type.

The coordinate measuring machine initially defines the coordinates of a spatial point in the machine coordinate system. However, these coordinates can also be converted to any other coordinate system, e.g. one which is oriented on the workpiece itself.

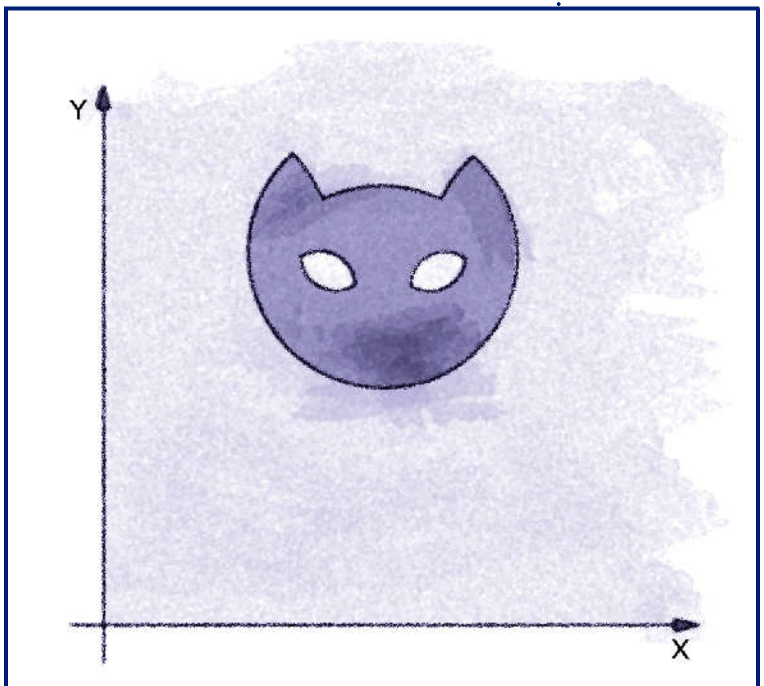


Coordinate planes

Coordinate planes are important for describing the location of objects in space. Two coordinate axes describe a single plane:

- The X and Y axis form the Y/X plane,
- The Y and Z axis form the Z/Y plane,
- The Z and X axis form the X/Z plane.

Coordinate planes are important in coordinate metrology because they are used to specify the direction of a straight line in space (as well as the direction of a vector): This is achieved by determining the angles at which the straight line intersects the coordinate planes. For more details, see *“Projected angles” on page 4_47*.



X/Y coordinate plane

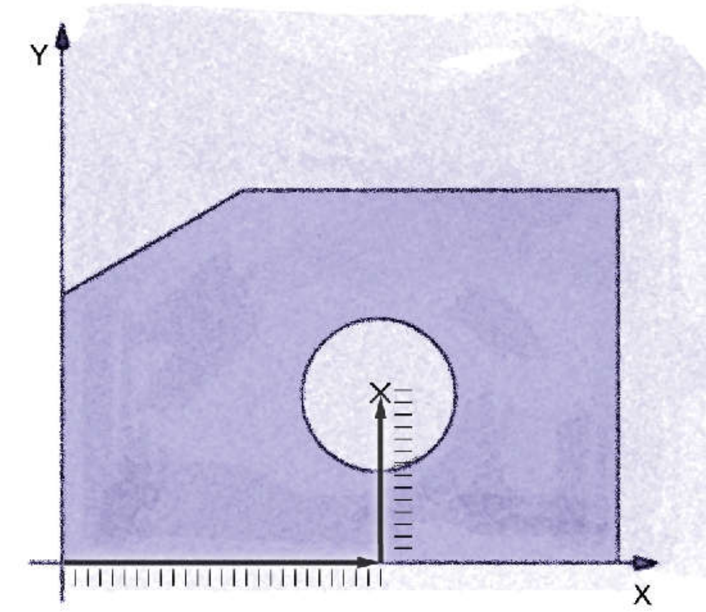
Coordinate planes are always shown in drawings as if viewed from a perspective directly opposed to the third, unspecified axis. I.e. the viewer seems to be looking directly "at the tip of the arrow head" of the third corresponding axis from the front.

The illustrations on the left show the position and the representation of the X/Y plane. Don’t be confused by the direction of the Z axis – a coordinate system can also have such an orientation. In most cases, however, the Z axis will point upward.

Planar coordinates

If the points on a flat or planar workpiece are specified with coordinates, this is referred to as *dimensioning*.

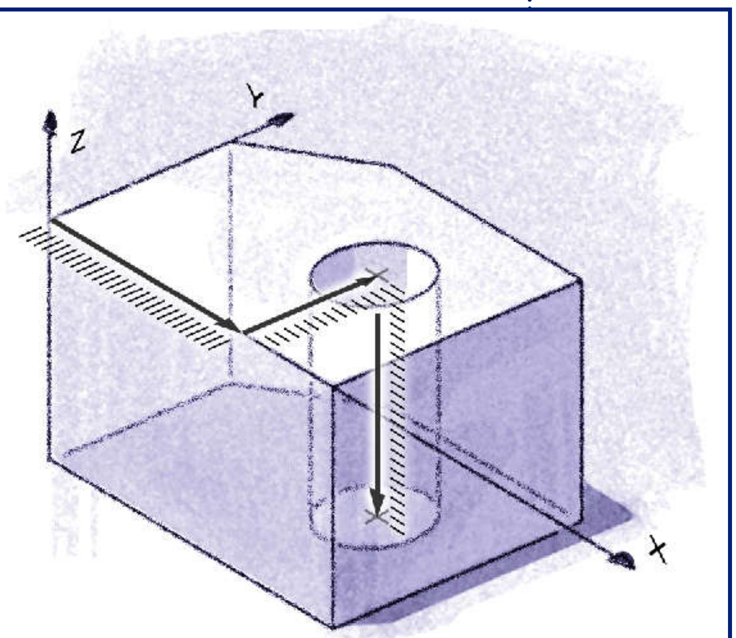
In the example shown on the left, the X axis is located along the longer edge and the Y axis runs along the shorter edge at a 90° angle to the X axis. Of course, each axis has its own separate scale. As with the city map, the coordinate pair (20, 40) specifies a location: If you start at the zero point, i.e. the origin of the coordinates, move 20 mm to the right (in the direction of the X axis) and then proceed 40 mm in the direction of the Y axis, you will reach the desired point.



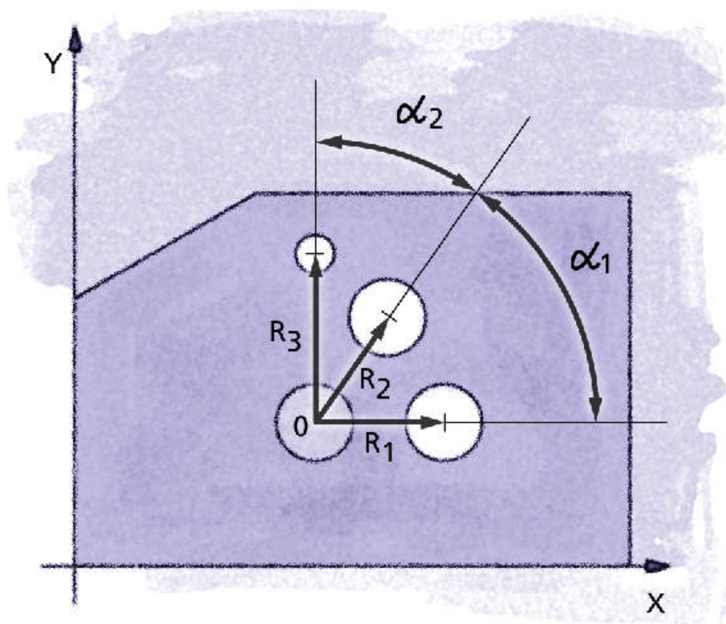
Planar dimensioning of a workpiece

Spatial coordinates

Coordinates are used exactly the same way in three dimensions. If the points of interest do not lie on the surface of our workpiece, an additional dimension is required: the Z axis. Three numbers are therefore specified. These three coordinates (e.g. 20, 40, -5) mean: Starting from the zero point, move 20 mm in the direction of the X axis, 40 mm in the direction of the Y axis and 5 mm "downward", i.e. opposite the Z axis. In our example that might be the depth of a drill-hole.



Spatial dimensioning of a workpiece



Polar coordinates

Polar coordinates

The Cartesian coordinate system is not the only one used. If the elements to be measured are grouped around an origin (e.g. drill-holes), it may be easier and make more sense to specify the *radius* and *angle*.

- Planar polar coordinates

  With **planar polar coordinates** the location of a point is specified in terms of its distance from zero point 0 (the pole), i.e. its radius is specified along with the angle between the ray extending from the zero point to point P and one axis.

- Spatial polar coordinates

  With **cylindrical coordinates** "height Z" is simply added to the planar polar coordinates.

  With **spherical coordinates** the location of a point is specified by the angles between the ray extending from zero point 0 to point P and two axes at right angles to each other as well as by the length of this ray.

One example of a spherical coordinate system is the familiar method of indicating points on the surface of the earth in terms of their longitude and latitude. The length of the ray from the origin (the center of the earth) is not, however, required here since it is here self-evident that these values refer to points on the surface of the earth.

Polar coordinates on a workpiece

If a working drawing specifies distances and angles, it is obviously practical to use a polar coordinate system.

A point of origin or "pole" must be determined for this purpose. An imaginary line is then drawn from the pole to the point of interest. This line has a definite length and forms a definite angle with a preferred direction, the polar axis.

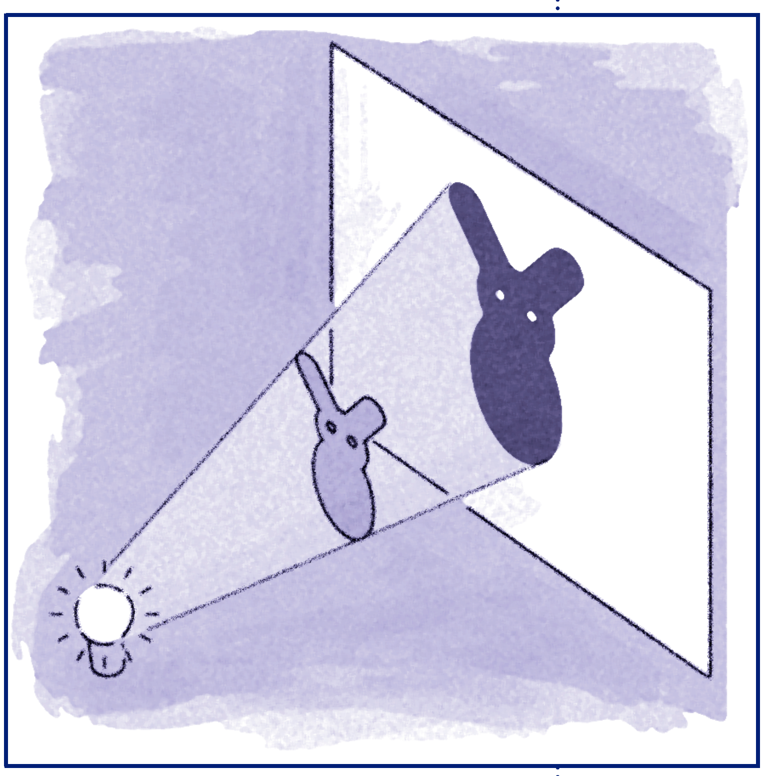
It is easier to convert coordinates from one system to another if this polar axis coincides with a coordinate axis of the Cartesian coordinate system.

The coordinates of the point are called

- Distance (radius) R
- Angle α

The angle always indicates rotation proceeding from the polar axis in a "mathematically positive direction" i.e. counter-clockwise.

Projected angles



Now you've learned quite a bit about the basic mathematics involved. But what about projected angles?

Projection

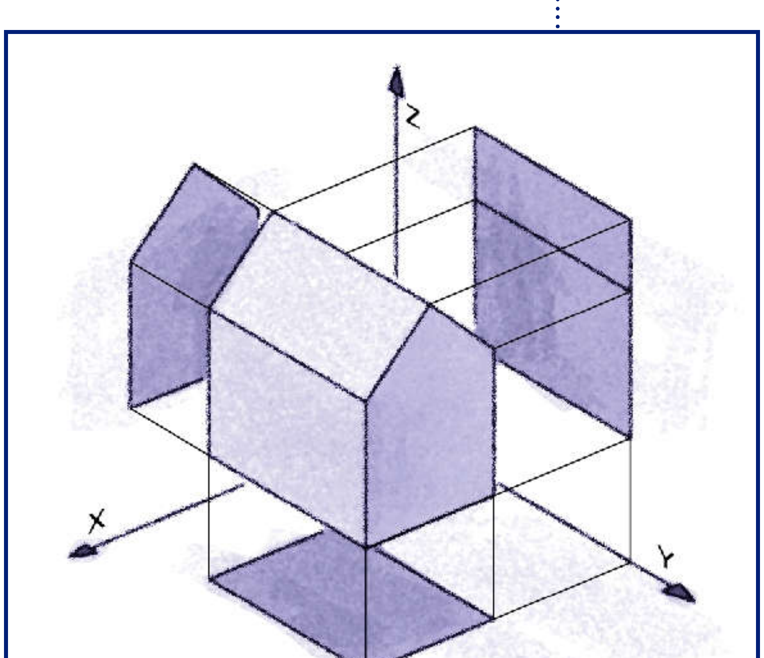
What is a projection? Let's take an example all of us are familiar with: a slide projector. As we know, this device produces an image using rays of light which pass through a partially transparent slide and then impinge on a plane, e.g. a projection screen.

The term 'projection' is used in exactly the same sense in geometry. A three-dimensional object which we imagine to be transparent is illuminated by rays of light. The shadow thus cast on the projection plane constitutes the projection of the object. The term 'projection' here refers to both the procedure and the result.

? Projection

The projection of a point is the point where the lines of projection intersect the projection plane. The projection of a geometric object is the set of projections of all its points.

One method of projection in which all light rays originate from a common center is a *central projection*. However, another method referred to as **parallel projection** is more important to and more commonly used in technology. In a parallel projection, all projection lines run parallel to each other.

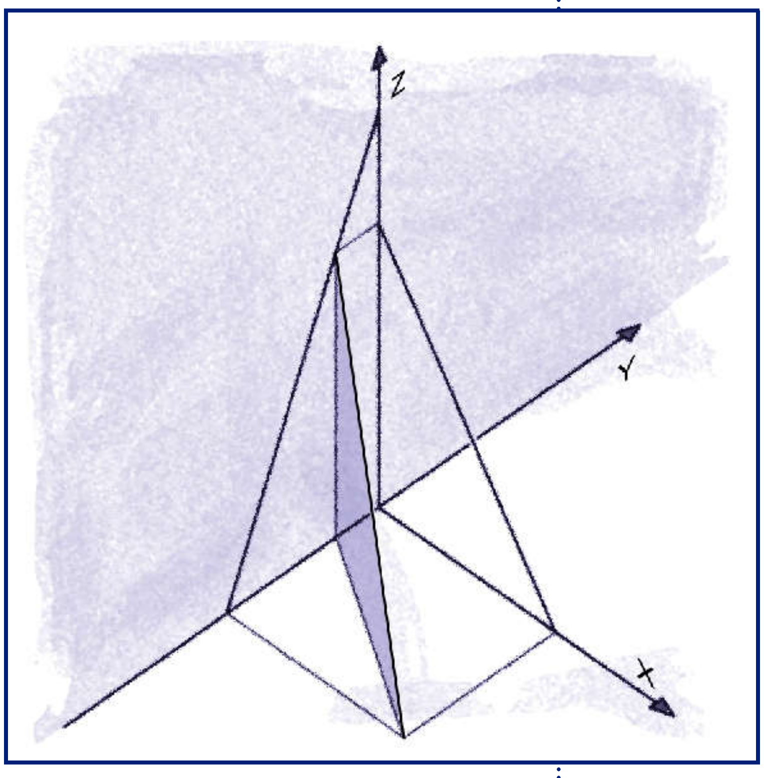


The ground plan and front views are projections

Example: front views and ground plans

Everyone is familiar with one type of projection: If we project an object along the coordinate axes and onto the coordinate plane perpendicular to the respective axis, both its *ground plan* or horizontal projection and its *front view* or vertical projection are thus obtained.

By the way: A dimension can be lost in the projection of an object. For example, the projection of a triangle is also a triangle unless the direction of projection is parallel to the plane in which the triangle is located - in which case the projection is a line.



Projected angles

"Projected angles" are used in coordinate metrology to exactly specify the *direction of a line* in three-dimensional terms.

The *inclination of a plane* can be clearly defined by specifying its normal vector. For this reason, projected angles are also suitable for characterizing a plane.

How are these angles formed? The projection of a straight line is generally also a straight line (unless it lies parallel to the direction of projection, in which case it is a point). Angles formed by the projections of lines and a coordinate axis are called projected angles.

Since there are three coordinate planes with one projected line each and two coordinate axes lie in each of these coordinate planes, a total of six projected angles are formed. However, only two of these angles are sufficient to clearly define the position of a line – all other angles automatically result from these two.

Ref. axis	Angle α1 in the	Angle α2 in the
X axis	Y/X plane	Z/X plane
Y axis	Z/Y plane	X/Y plane
Z axis	X/Z plane	Y/Z plane

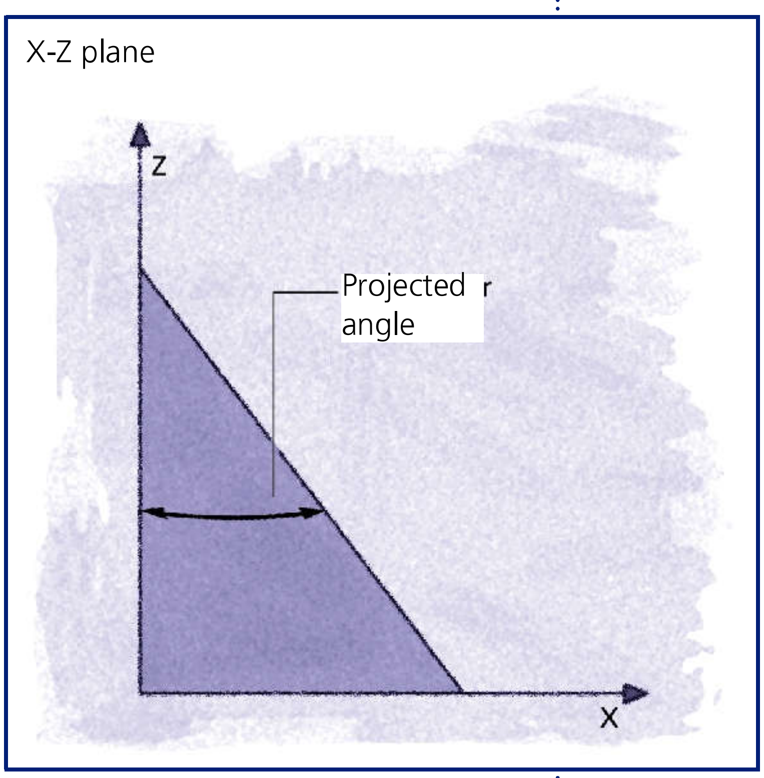
Reference axis

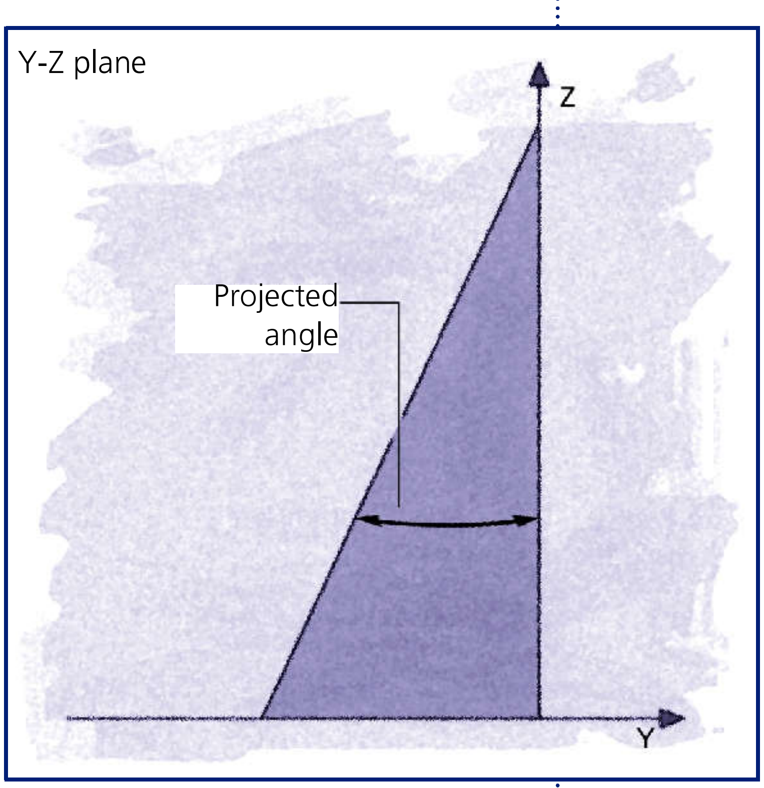
But how are these two angles selected? It is generally understood in coordinate metrology that the coordinate axis which together with the respective line forms projected angles between -45° and +45° is also used to specify the projected angles.

By the way: *at least one* such axis always exists!

The axis thus selected is called the **reference axis**. This reference axis defines two coordinate planes. The two angles which are formed by the two projections of the lines located in both of the coordinate planes defined by the reference axis are the ones which are calculated or specified as the projected angles.

As complicated as this may sound at first, it becomes clearer after considering the following example:





Example

The Z axis should be selected as the reference axis. It defines the two coordinate planes, X/Z and Y/Z. A straight line not parallel to the Z axis and the direction of the Z axis jointly define a plane which is parallel to the Z axis and contains the straight line.

The illustration on the previous page shows exactly such a line with an "oblique" orientation in space moving toward the Y/Z plane. The plane mentioned above defined by the straight line and the "direction of the Z axis" is depicted here as a shaded triangle.

The line and the direction of the Z axis form an angle in this plane (which is the top acute angle of the triangle).

This angle is projected onto both the X/Z and the Y/Z plane. Two "projected angles"are obtained in this manner.

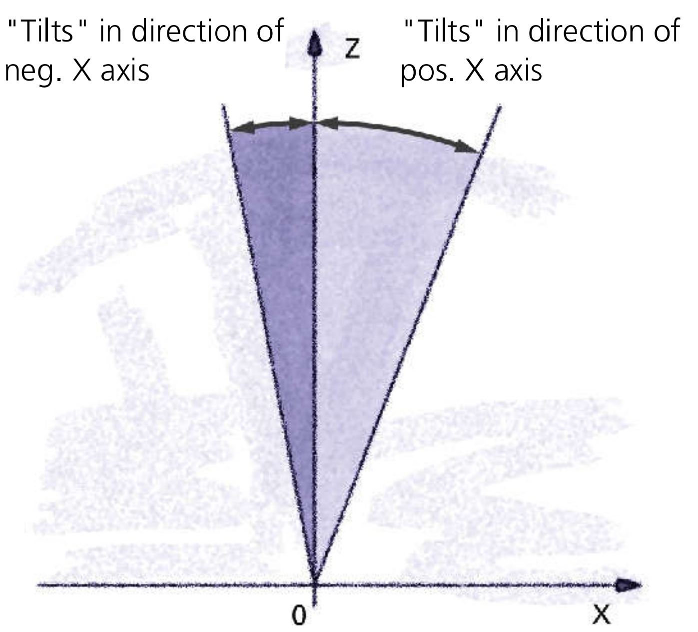
Think once again about what projection means: You illuminate the angle once along the Y axis to obtain a shadow in the X/Z plane. Then you illuminate from the direction of the X axis and obtain a shadow – the projection – in the Y/Z plane.

You can see this shadow in the two illustrations on this page: the projections of the triangle from the first illustration. The projected angles are acute angles where the extensions of the projected lines intersect the Z axis.

Notation

If you want to characterize a line, vector or plane by specifying projected angle $\alpha 1$ or $\alpha 2$, you must of course also specify the respective coordinate plane to make your reference unambiguous. This is notated e.g. as follows:

- X/Z $\alpha 1$ –35.3024
- Y/Z $\alpha 2$ 25.0298



Projected angles in the coordinate plane

What do negative angles signify?

The angle formed between the projected lines and the reference axis is specified as the projected angle. Expressed in mathematical terms, this means that the angle is measured "counter-clockwise" (= in a mathematically positive direction) from the projected lines to the coordinate axis.

A positive projected angle therefore means that the projected line runs in the coordinate plane from the "bottom left" to the "top right" (into the first quadrant).

On the other hand, a projected angle with negative sign means that the projected line runs from the "bottom right" to the "top left" in the coordinate plane (into the second quadrant).

As a rule of thumb, just remember that a projected line with a positive angle in the coordinate plane of the reference axis "tilts" in the positive direction of the second axis, while a projected line with a negative angle "tilts" in the negative direction of the second axis.

How is the direction of the vector described?

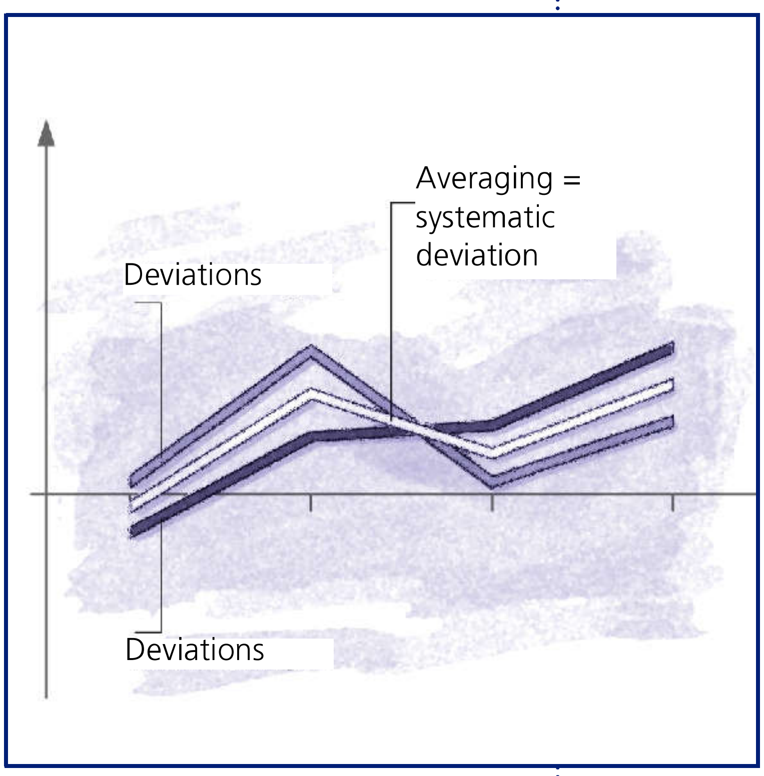
You can also specify the positions of vectors, e.g. of normal vectors, using projected angles. At the same time, you must also take into account the fact that not only the position information, but also the directional information must be specified.

How do we then differentiate between the two possible vector directions along one and the same line?

The normal vector concerned can be represented by a directional line, i.e. a "straight line with an arrow".

In coordinate metrology there is a general convention for specifying the projected angle concerned in the respective coordinate plane which states that the reference axis must be indicated with a minus sign (–) if the "arrow" of the projected line is pointing "downward", i.e. in the negative axial direction.

Measuring errors and deviations



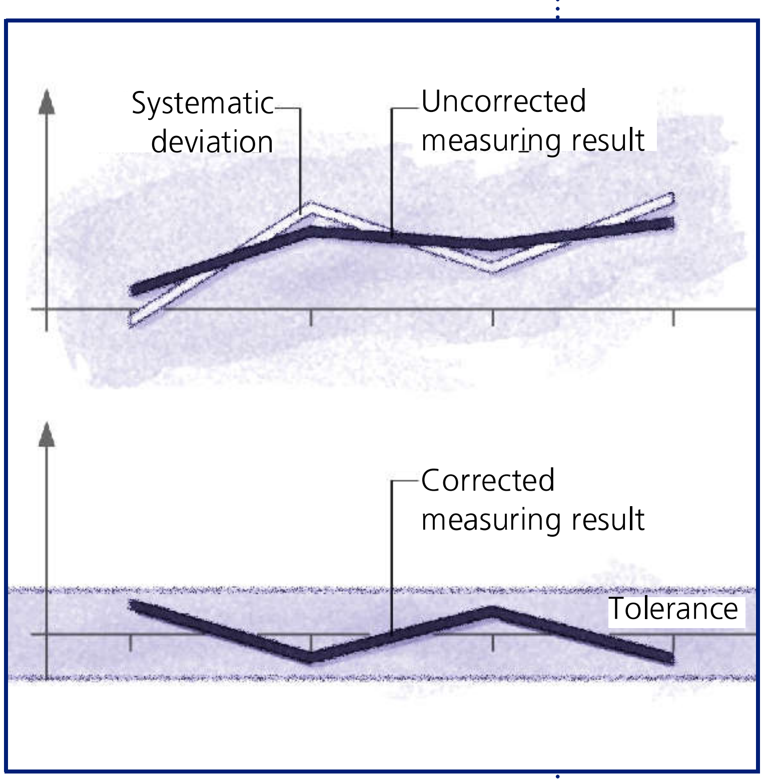
Despite all efforts to achieve maximum accuracy and the technical tricks we use, every measurement yields a value which deviates more or less from the actual dimension. The reason for this is that physical phenomena otherwise only of minor importance, e.g. temperature fluctuations, play an entirely different role in connection with this order of accuracy.

The deviation between the value actually measured (or assigned to the measured variable) and the (unknown) true value of a quantity to be measured is called the *measuring error*.

This measuring error comprises a systematic and a random measuring deviation.

Systematic measuring deviation

The systematic measuring deviation is that part of a measured value's deviation from the actual value which is caused by the technical implementation or measuring technique and always occurs with the same amplitude and direction under the same conditions.



It may be due to certain inaccuracies of the measuring instrument resulting from

- its manufacture (e.g. inaccurate machining of the guideways on the granite table) or
- the technique used (e.g. systematic minimum sag of a rail caused by the applied weight).

?CAA

__C__omputer __A__ided __A__ccuracy: Process for automatically taking systematic deviations into account through high-precision measurement.

Since the systematic measuring deviation always remains the same under identical conditions, it is repeatable. For this reason, the systematic measuring deviation itself is also to a certain degree measurable - and therefore correctable.

This correction is performed automatically - the whole process is called **CAA**. Today every CMM utilizes this method to increase its accuracy.

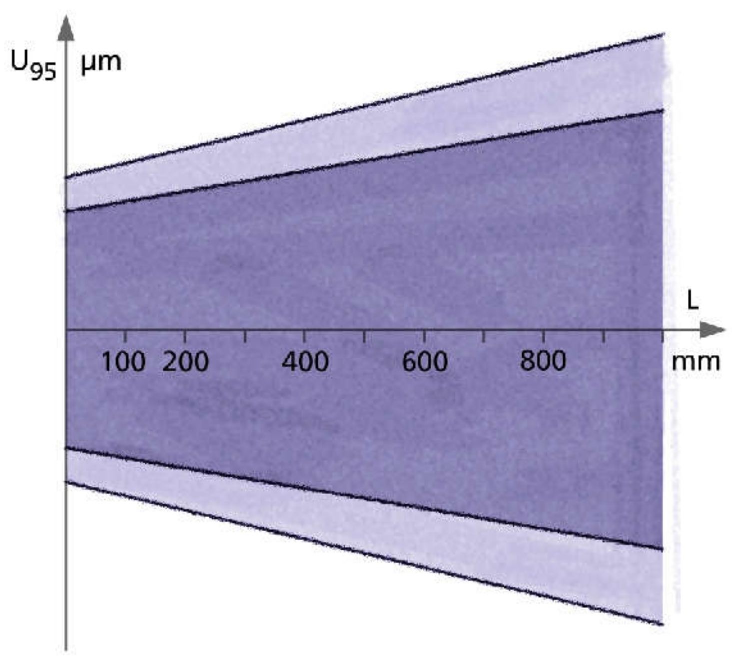
Random measuring deviation

A random measuring deviation is an additional coincidental deviation of the measured result from the actual value. Even the smallest random deviations, e.g. air currents, vibrations, dust particles or temperature fluctuations may lead to measured values which repeatedly vary slightly from one measurement to the next.

Systematic and random measuring deviations are cumulative and always occur together. While the systematic deviation can be determined by measuring high-precision testpieces and then mathematically compensated for, this procedure can not be applied to a random measuring deviation.

It is, however, possible to estimate the amount of the random measuring deviation and then define a tolerance range within which the actual, true value can be assumed.

Length measuring uncertainty U_{95}



Measuring uncertainty of a CMM

The measuring uncertainty can be defined as the tolerance range which contains the measured value finally specified and can be assumed to contain the true value as well.

But not, of course, with absolute certainty – which is the reason why the percentage of measurements which can be guaranteed to fall within this tolerance range is always specified along with the tolerance range. The measuring uncertainty usually specified is U_{95}, which means that the tolerance applies to 95% of all measurements.

The width of the tolerance range depends on the machine and is proportional to the size of the distance to be measured. For this reason, the accuracy of a CMM is usually specified by only two machine-typical constants which can be used as a basis for calculating the tolerance for a given length. The formula for this calculation is:

$U_{95} = k_1 + 1/k_2 * L$

The smaller k_1 and the greater k_2 are, the more accurate the CMM is.

Example: k_1 equals 1.5 µm, k_2 equals 400 mm/µm. If the length to be measured equals 200 mm, tolerance U_{95} amounts to exactly 2 µm, since:

U_{95} = 1.5 µm + 200/400 µm = 2.0 µm

Thus if you know the value of k_1 and k_2, you also know the tolerance, and therefore the measuring uncertainty, for every distance.

Since the tolerance corresponds to the possible positive or negative deviation, the above formula defines a funnel-shaped pattern also known as a "trumpet curve".

Statistical terms

Statistics deal with laws which are applicable to large numbers of (possibly incorrect) measurements.

Mean value

The mean value of a series of measurements or results is calculated like the average. The mean value is calculated as the sum of all values divided by the total number of values. However, while the average (e.g. a student's average grade in a given subject for a school year or the average depth of a river) is based on measurements taken from different objects at different times and/or places, the mean value refers to repeated measurements of one and the same thing (e.g. individual evaluations submitted by the judges at a figure skating competition).

The mean value already gives us a general idea of where the actual value could lie. The dispersion provides information on how far the mean value might deviate from the actual value.

Dispersion

If you poured out the contents of a sugar bowl onto a table, the sugar would scatter on the tabletop. The farther away from each other the individual grains of sugar lie, the greater their "dispersion" .

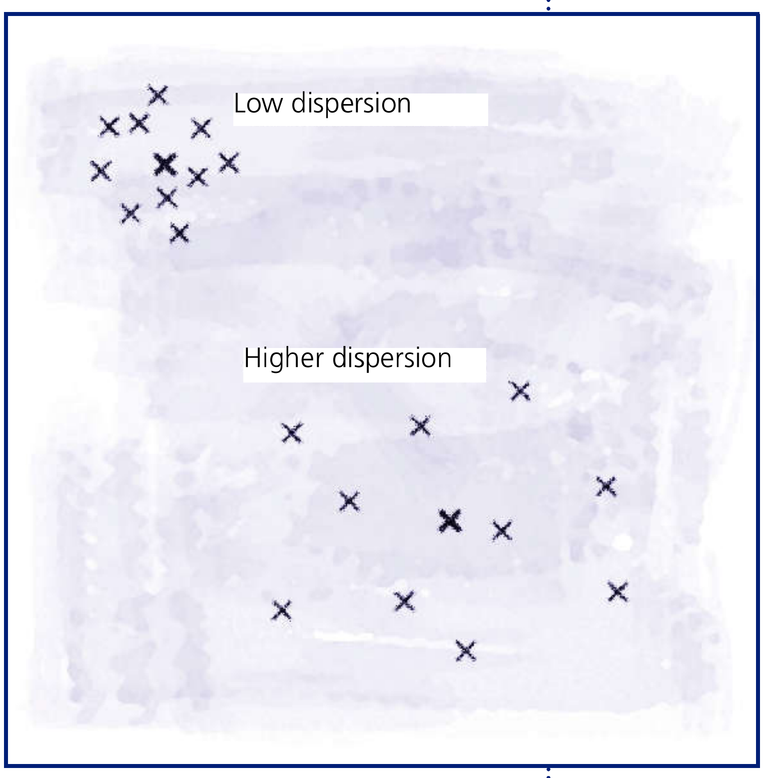
In statistics, the dispersion also indicates how far away from each other measurements influenced by coincidence lie. As a result, it also gives us an idea of how exact the results of the measurements are.

When dealing with many different points of a geometric object measured to a specific accuracy, you need information on the reliability of the measurements. The dispersion can provide valuable information in this regard.

The square of the dispersion, σ^2, is the mean value of the squared differences (deviations) of all measured values x_i from the mean value determined for these measured values, $\bar{x}$.

$\sigma^2 = 1/n \, \Sigma \, (x_i - \bar{x})^2$

The dispersion σ (sigma) can thus be calculated from the square root of this number.



Why determine the dispersion?

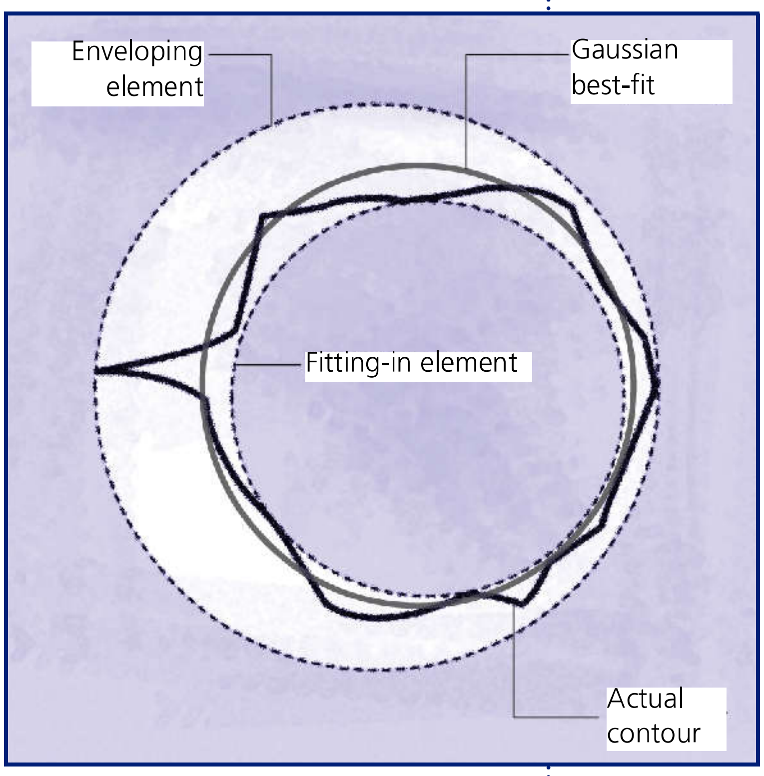
The closer the individual measurements lie to their mean value, the smaller the dispersion and the probable deviation of the mean value from the value actually measured will be.

If the dispersion is too great, the value determined can not be assumed to be the actual value with sufficient certainty - i.e. may be outside of the desired tolerance range.

In metrology it is generally assumed that the dispersion should be less than two times the **resolution** of the measuring system. Example: The resolution of the measuring system equals 0.5 micrometers. The dispersion must be less than 1 micrometer. If a higher value is determined during probe calibration, the data may be useless and the probe calibration should be repeated.

? Resolution

The CMM's most exact measuring or dimensional capability.



Gaussian best fit

The dispersion is also used by the computer software to define curves or forms. For example, if we measure several contour points of a circular drill hole, they will generally not lie exactly on a theoretical circular line. How can the parameters of the circle (center point and radius/diameter) then be defined? Or, to put it differently: How can we *best-fit* a circle into the measuring points?

One of the most frequently used best-fit methods is the **Gaussian best-fit**. In this case, the form element (i.e. here the circle) is selected so that the dispersion, i.e. the sum of the squares of the deviations of the measuring points from the form element, is minimized. This is no problem for the software.

Other methods define the **minimum circle** (largest circle which all measuring points lie outside of) as the **fitting-in element** (maximum inscribed circle) or the maximum circle (smallest possible circle which all measuring points lie "inside of" as the **enveloping element**. (minimum circumscribed circle).

When selecting a best-fit method to determine a measuring element, always take the function of the workpiece and your objectives into account. If you e.g. want to ensure that pins of a specified diameter will always pass through a drill-hole, the fitting-in element is advisable.

What you should know now

What is the normal vector in a point and how can it be specified?

Explain the structure of a Cartesian coordinate system and how is it used:

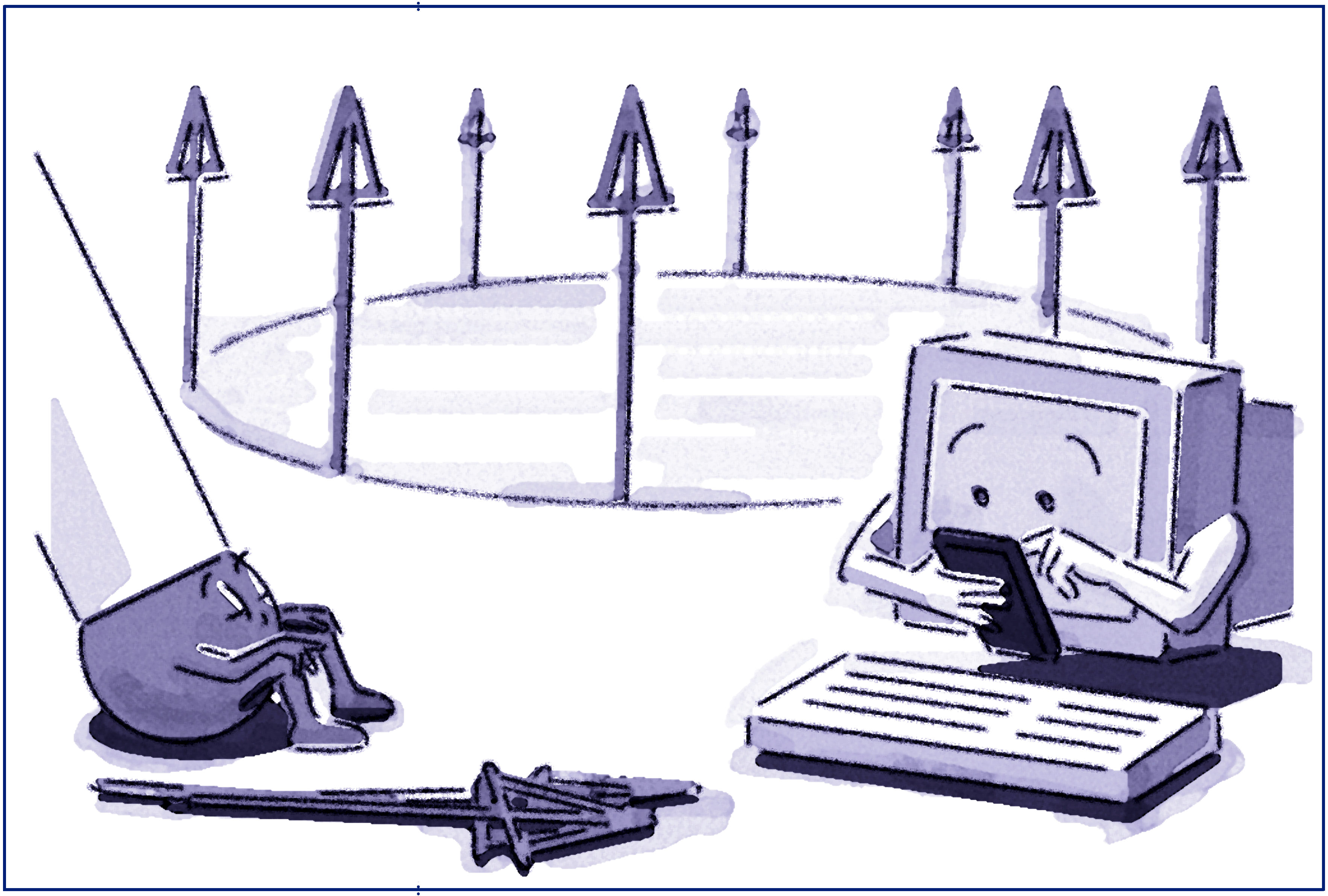
How are projected angles generated and how are they displayed and specified?

What does the measuring uncertainty of a coordinate measuring machine mean?

Why do we need the dispersion value for a series of measured values?

5

From probing to measuring result



In this chapter you'll read exactly how "raw" probing data is further processed to obtain measuring results and just where you come into the picture.

For example, all probing locations and the order in which points are probed must be carefully defined.

In addition, the value generated by the probing must be further processed to obtain the actual measuring result. In other words, the computer must consider the position of the workpiece, the systematic deviations of the CMM, and the features of the probe combination as well as the object being measured.

Components of the measuring result

Systematic deviations

Constantly recurring directional and dimensional measuring inaccuracies caused by manufacturing and assembly deviations of the CMM, minimal deformation etc.

Probe calibration

Probe calibration: each probe must be calibrated i.e. defined with regard to its position before use. The differences in position and size between the probe and master probe are determined in the process.

When the CMM has determined the probing location with the help of the length measuring systems, the computer still must perform a few corrections and conversions i.e.:

- Machine-specific **systematic deviations** must be "compensated out".
- The values from the **probe calibration** must be included in the calculation.
- If the probing can not be performed exactly at a 90° (right) angle to the surface of the workpiece, the location determined must be corrected accordingly.
- Finally, the coordinates determined in reference to the CMM are converted to a coordinate system which is referred to the workpiece.

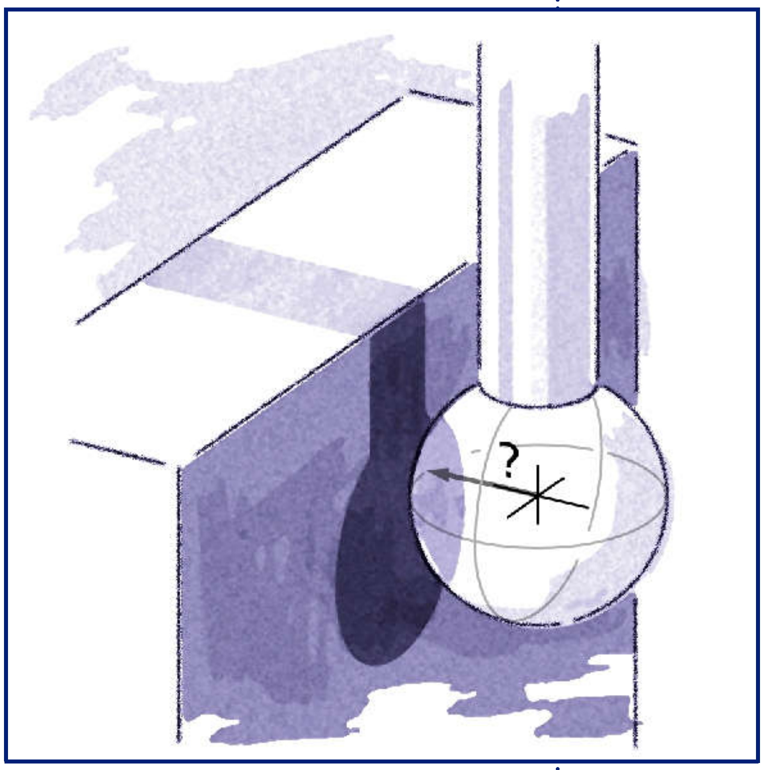
The following sections explain these correction and conversion processes in more detail and show where the required correction data comes from.

In addition, you will also find out what you can do to influence the meaningfulness and the accuracy of the measuring results.

Acquisition of measured values

Master probe

A specially marked probe delivered along with the CMM with dimensions which are known to the CMM and calculated into the measuring result.



The length measuring system always determines the same location, regardless of the probe used and/or the direction in which probing is performed: This location is usually the center point of the sphere on the **master probe**. It is not, however, the probing location.

Probe correction

To ensure that the correct value appears on the control console or the screen of the external computer, the following data must be taken into consideration by the control or the computer software:

- Which probe was inserted?

  You, i.e. the user, must input this information to the CMM - unless of course the probe is automatically retrieved from a probe magazine (CNC probe change).

- In what direction was probing performed?

  This can be determined by the CMM based on the direction of travel. It is generally assumed that a probing point will be approached in a direction which is at a 90° angle to the surface being probed.

- Which probe was used for probing?

  If the probe has more than one stylus, you must input this information to the CMM.

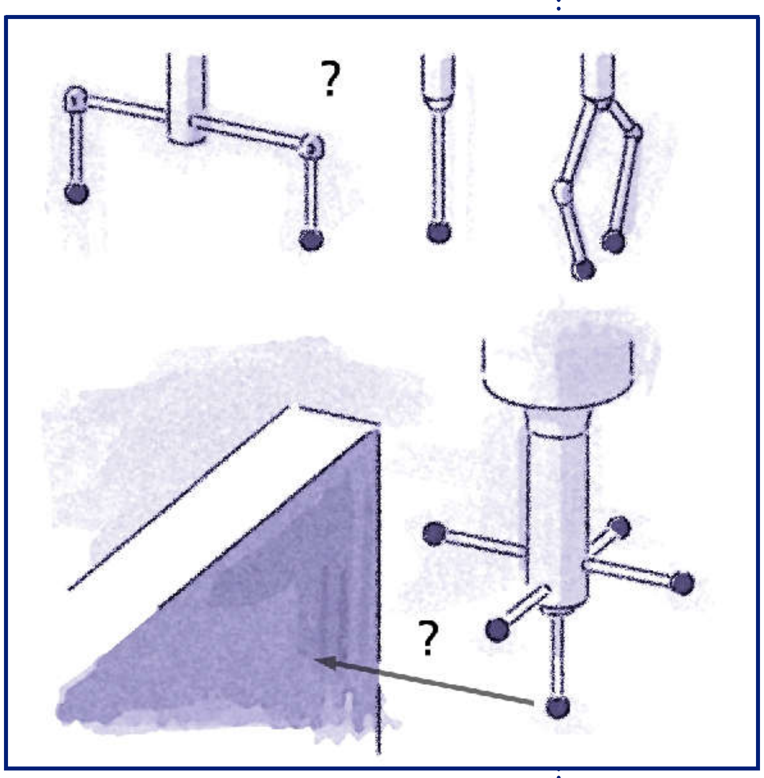
- What is the radius of the probe tip (i.e. sphere) used for probing?

  Since the end of the stylus can not be an "ideal point", the radius of the probe tip attached to it must be either added or subtracted (depending on the probing direction).

The computer must note where the end of each stylus is and the radius of the probe tip (sphere) for each probe. Once this data has been determined and saved once for each probe, the probe can then be quickly changed without any complicated recalibration. The software can then take the probe being used into consideration.

Probe changing can also be left completely to the CMM if an automatic probe changer magazine or rack is installed. The CMM then has everything under control.

Probe calibration



A probe may have any number of styli – the limiting conditions are its maximum weight and its handiness. The individual styli are fastened to the probe adapter e.g. in a star-shaped configuration. Fastening elements, extensions and joints can be used to assemble workpiece-specific configurations to make specific points on the workpiece (more) accessible. The adapter holding the probe styli is inserted in the probe head.

In a programmed automatic measuring run, the machine "knows" which probe should be used for probing and automatically retrieves it from the storage rack.

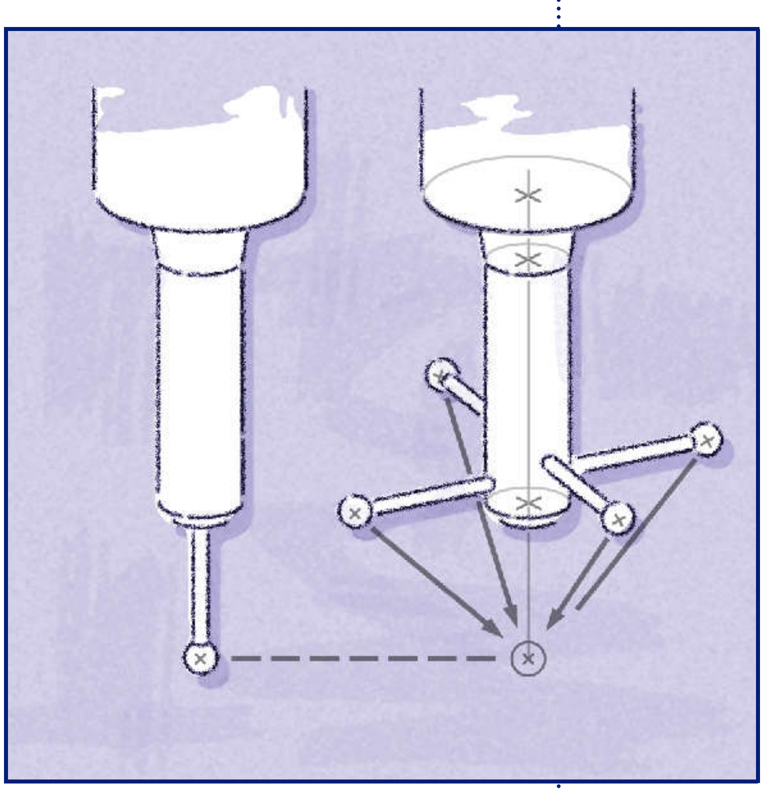
Why probe calibration?

To ensure that the different probe styli produce identical measuring results during subsequent measurements, the computer must be provided with the following *beforehand*:

- How the individual styli are spatially arranged in relation to the master probe,
- The radius of the probe tips.

And that is exactly what happens during *probe calibration*.

Following calibration, the computer knows the center-to-center distances between the probe tips, the center-point of the master probe tip and the diameter of the probe tips.



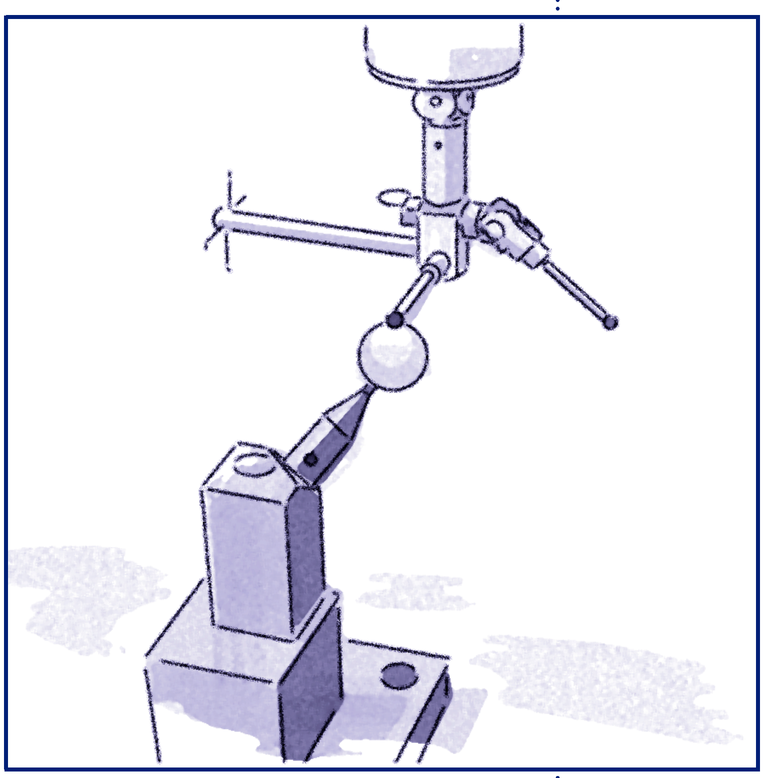
Calibration standard or sphere

A precision-shaped sphere is used as the *calibration standard*. Such a calibration or datum sphere has the following advantages in comparison to a gage block:

- It doesn't have to be aligned.
- It is accessible for probing in all directions.

The exact diameter of the sphere, which is an accessory to and delivered along with the CMM, is stored in the CMM computer.

The calibration standard is not only used to measure the radius of the probe sphere, but also to determine the relative position of the probe center.



Probe calibration procedure

Determine the location of the calibration sphere

The calibration sphere can be placed anywhere on the table or surface of the CMM. Then the computer must determine this location. This is done by probing the calibration sphere with a master probe whose location and geometry are known to the computer from several different sides according to a predetermined strategy. The computer then calculates the center point of the calibration sphere.

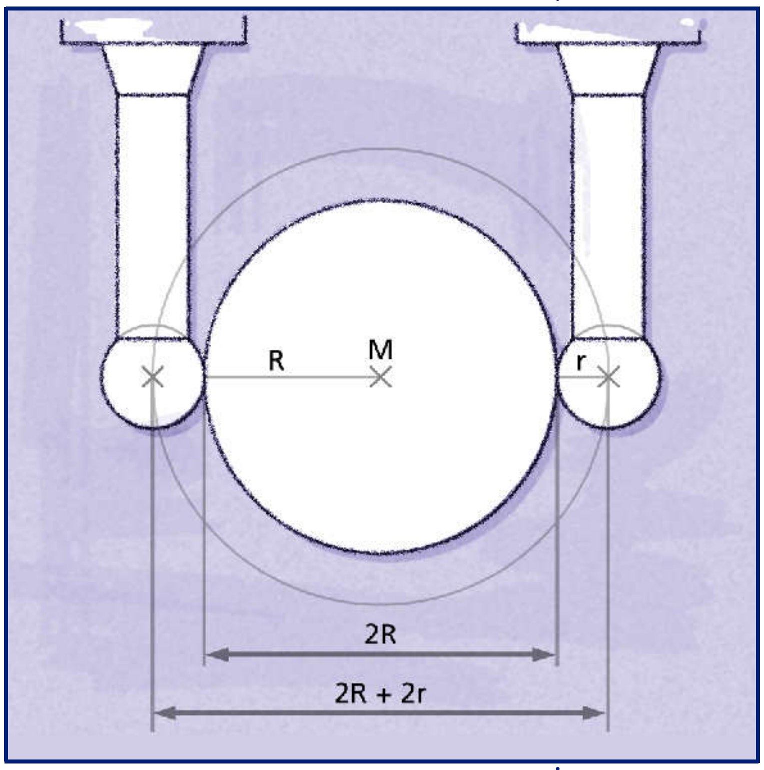
Calibrate geometry of the other probes

The calibration sphere must be probed with each probe to be used according to a strategy determined by the computer. Very important: during this process, the calibration sphere must of course remain at its calibrated location

Calculate the correction values

Based on the acquired data, the correction values are then calculated for each individual probe stylus:

- In the first step, the computer calculates the distance between the probe stylus and the master probe. A sphere and its center point are calculated based on these probings. The center point is of course "incorrect" since it would only be correct for the master probe. However, since the correct location is already known from the first measurement and the following calculation, the correction value required for the probe is derived from this value.



- In the second step, the probe tip radius is determined. The radius of the sphere calculated by the computer is larger than the exact, known radius of the calibration or datum sphere by an amount equal to the radius of the probe tip. The radius of the probe tip is therefore calculated as the difference between the "measured sphere radius" and the "stored radius of the calibration sphere".

Following probe calibration, the computer knows the data of all probes to be used for measurements.

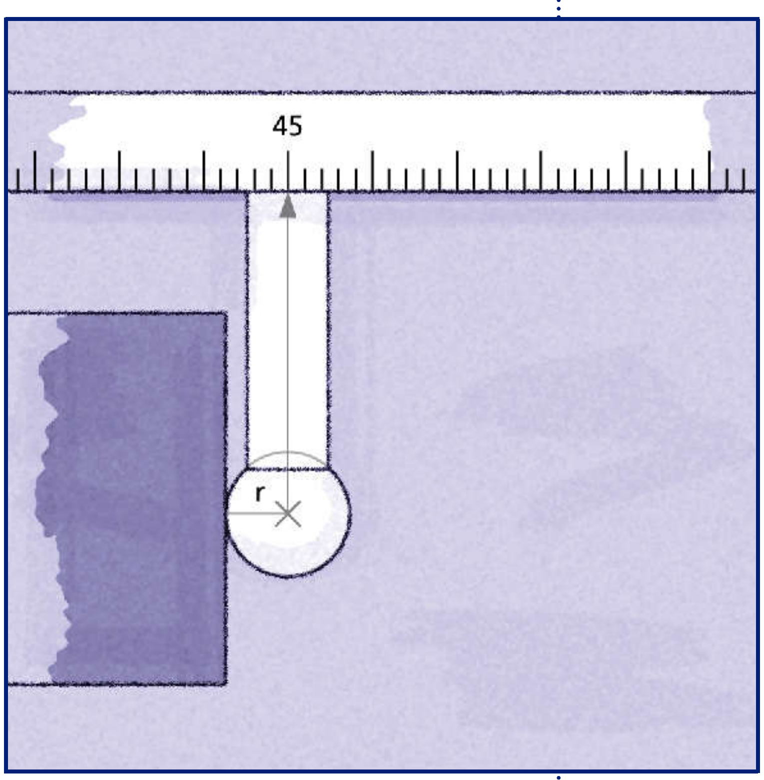
Probe calibration without the master probe

Probe calibration can be performed even if the CMM has no master probe. In this case, the first probe used to perform measurements on the calibration sphere is designated as the reference probe.

When probing the calibration sphere with all other probes, the computer then calibrates the position of the each individual probe tip's center point relative to the reference probe by calculating the difference between their machine coordinates.

This is possible since only the *relative* position of the different probes is important for correct evaluation of the probings.

Probe correction following a position measurement

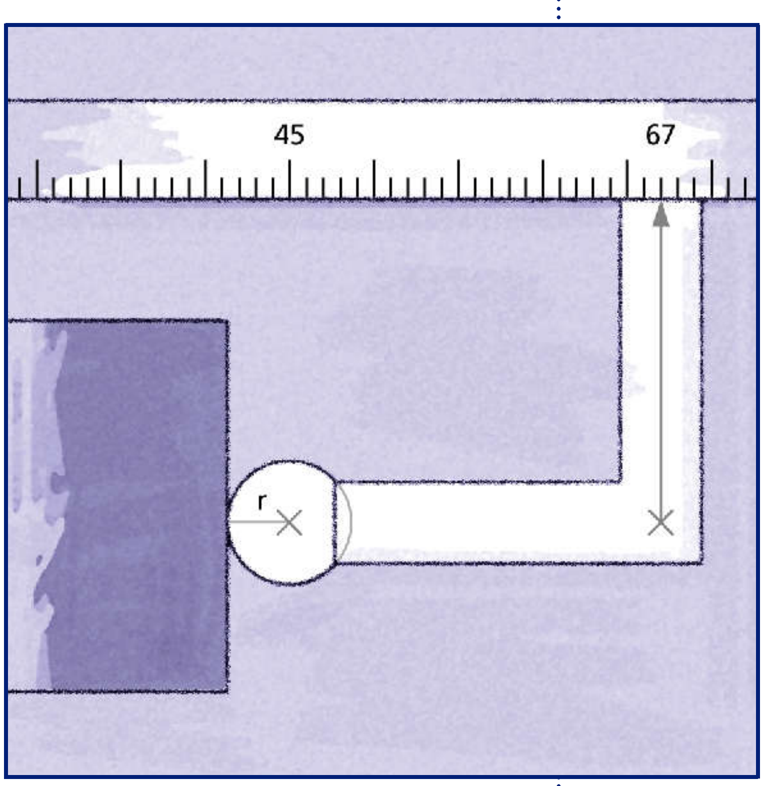


The type of probe used depends on the workpiece being measured - i.e. always take a good look at the workpiece and think carefully about how to proceed before calibrating probes.

During probing, the "location of the quill" is measured first. Then the probe-specific correction of the probe being used for probing is performed.

Take, for example, the following measurement of only a single coordinate axis.

Example 1: Probing is performed with the master probe. The computer subtracts the radius of the probe tip from the measured value of 45 mm.

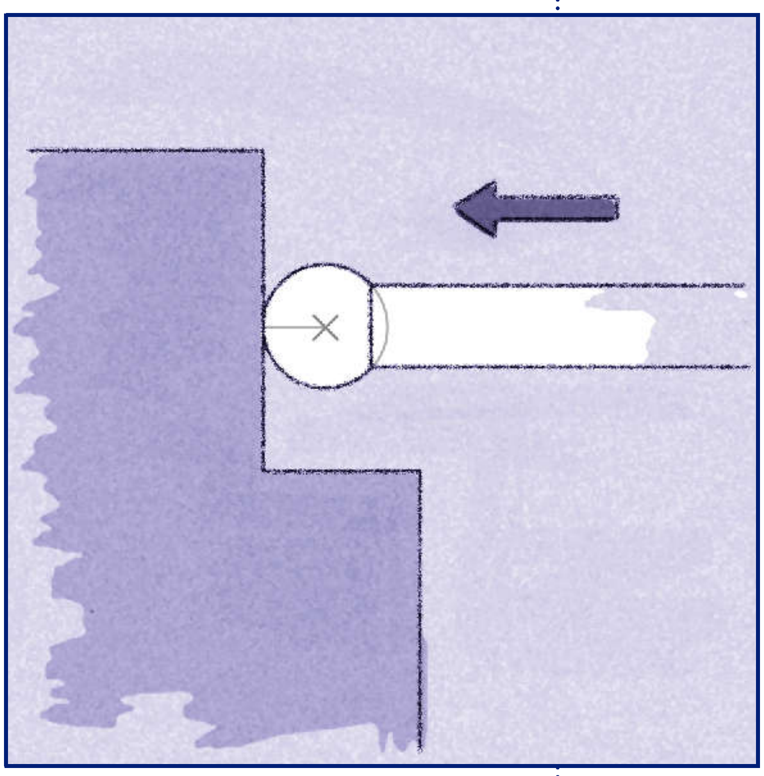


Example 2: Probing is performed with another probe. In addition to the radius of the probe tip, the computer also subtracts the distance between the reference probe and the probe being used, i.e. 22 mm, from the measured value of 67 mm.

Of course the computer also performs this correction in the same way for the other two axes.

By the way: you must select the probes to be used *before* you begin probing. Otherwise incorrect values will be produced.

Probing and probing direction



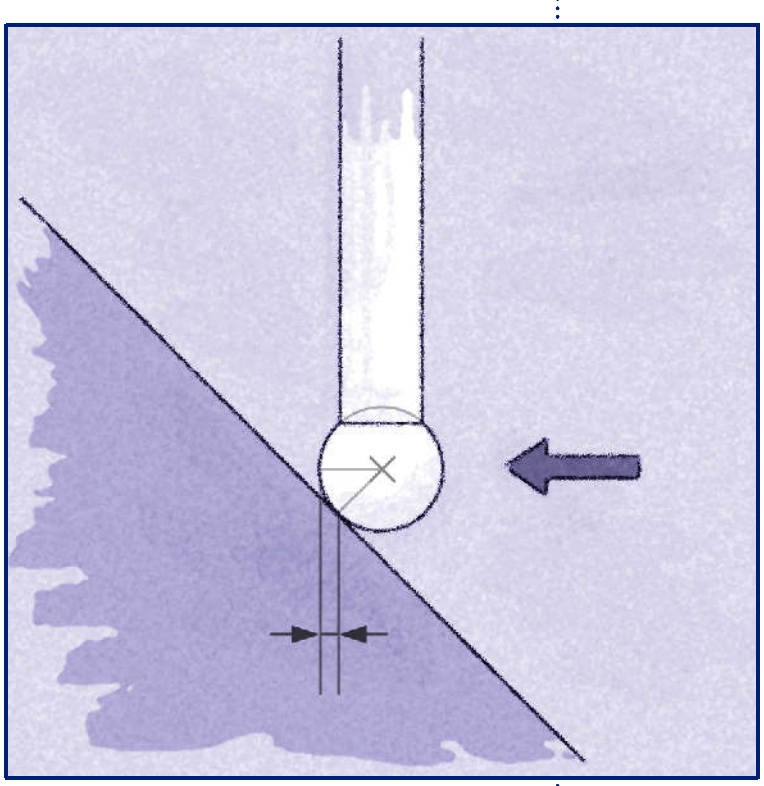
When the CMM stops on contacting the workpiece, the coordinates of the probing location are "read off" and transmitted for evaluation. The CMM here assumes that the point probed is located "straight ahead in the direction of travel", i.e. that the surface of the workpiece is at a right angle to the direction of travel at this point.

If the direction of the surface deviates considerably from the above orientation, the actual probing location will then deviate considerably from the assumed location.

Correction of the inclination error

The machine can correct this error only if it knows the surface inclination.

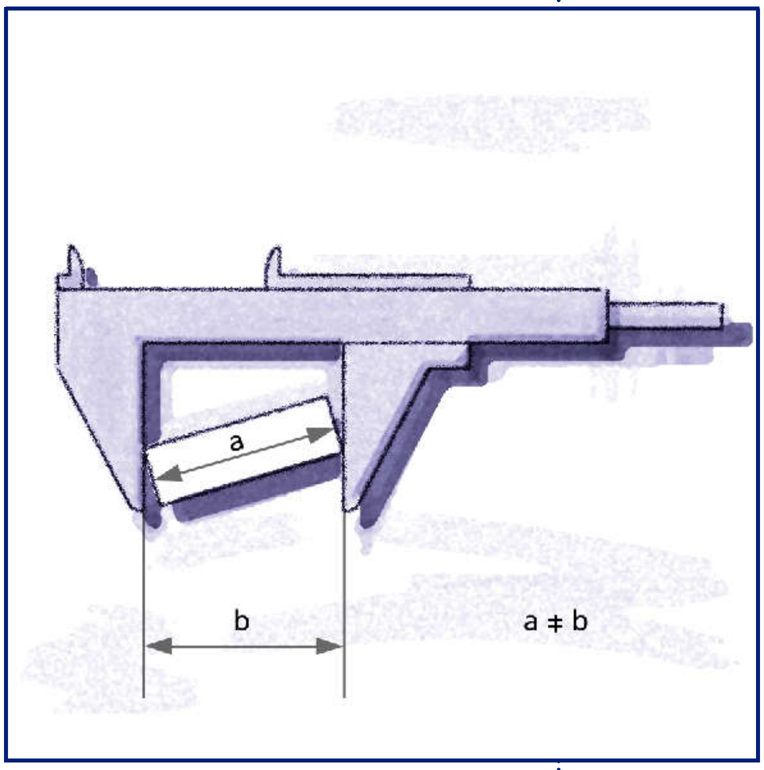
During a single-point measurement of an inclined surface, you must either also specify the inclination or determine this value through additional measurements.



On the other hand, the easiest solution is to perform a plane measurement. In this case, the software automatically calculates the inclination of the plane from the probing points and then corrects the individual measuring points.

In cases involving sculptured surfaces which are to be scanned, the software determines the approximate inclination of the tangential plane in the current probing point from the (preliminary) coordinates of the surrounding points and uses it to correct the value obtained. A multistage, repetitive correction process thus takes place in the computer here.

Mathematical alignment



Why align at all?

Since the workpiece is clamped, its planes lie more or less slanted in the CMM coordinate system. As a result, compliance with **Abbe's law** can not be ensured during measurement and a larger or smaller error (the so-called cosine error) may occur due to tilting of the workpiece.

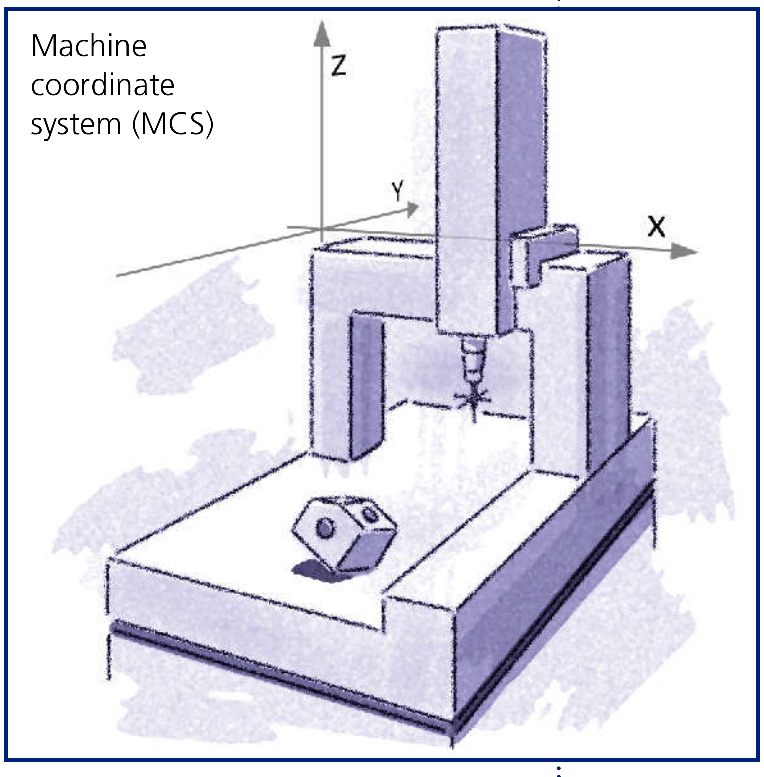
This could be remedied by physically aligning the workpiece exactly to the machine coordinate system (*mechanical alignment*). However, this process is very time-consuming and virtually impossible considering the required accuracy.

Another possibility would be not to align the workpiece to the coordinate system, but to align the coordinate system being used to the workpiece instead. However, the coordinate system referred to the workpiece must be created for this purpose first.

This procedure, which is commonly called *mathematical alignment*, functions much faster and more exactly than mechanical alignment. However, the most important advantage of mathematical alignment is that it can be automated!

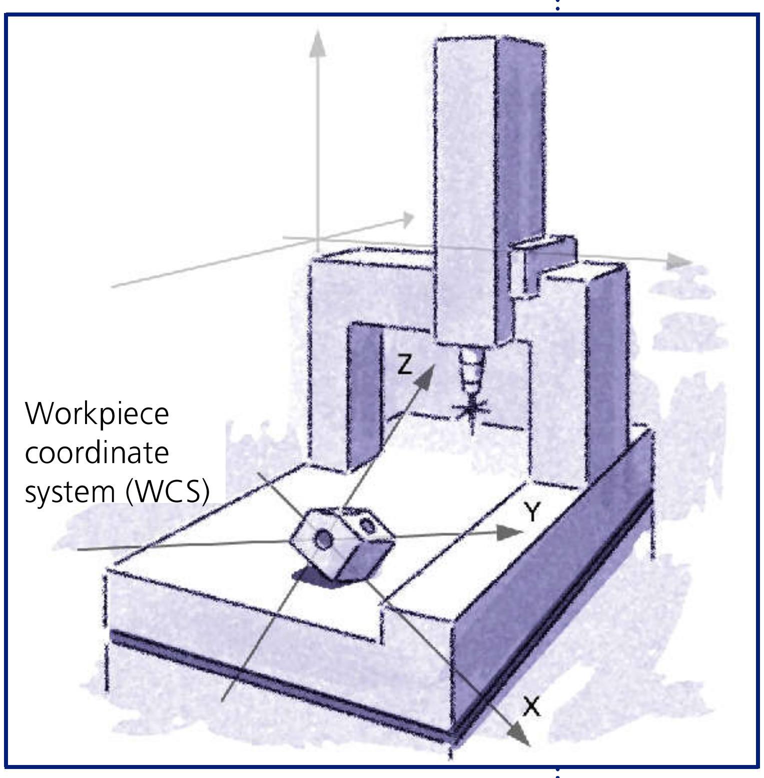
Abbe's law

To ensure the correctness of a linear measurement, the length measured and the reference scale must lie parallel to each other.



Mathematical alignment procedure

Mathematical alignment involves the creation of a separate "workpiece coordinate system" from elements of the workpiece.



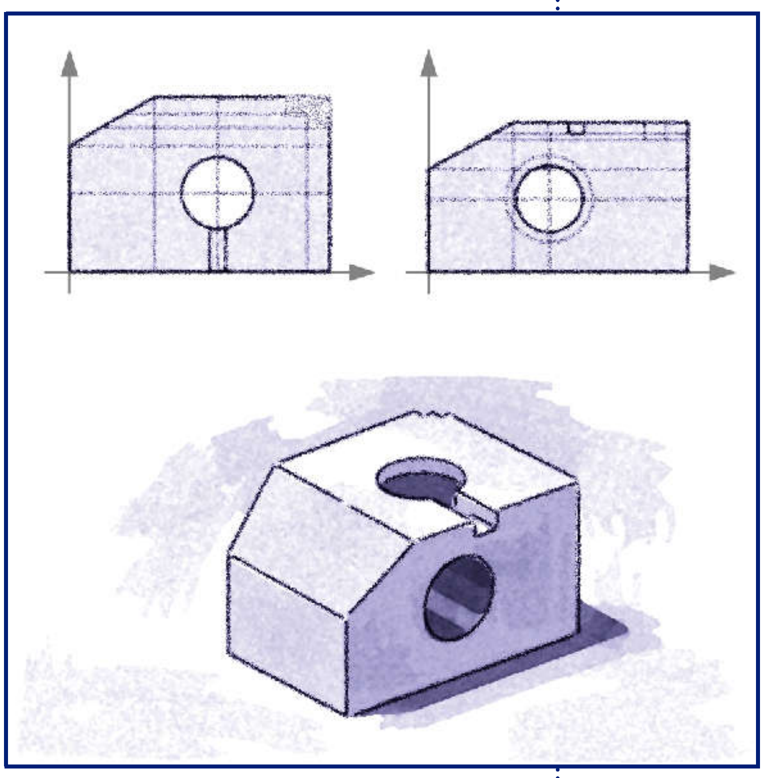
The computer can "know" this coordinate system only after it has been "introduced" to it. This is achieved by probing the points which define the new coordinate system. The data for the new coordinate system is then saved to the computer.

When the workpiece is then probed in order to measure it, the computer initially receives the coordinates in the machine coordinate system. This data is then converted to the workpiece coordinate system according to fixed conversion formulae and also output in that form.

Where does the new coordinate system come from?

Which elements of the workpiece determining the coordinate axes can be found in the working drawing?

If we align the workpiece coordinates according to the working drawing, this makes it easier to evaluate the measured and the output data, since they both then refer to the dimensions specified in the drawing.



In addition, this also makes it easier to recognize what must be changed in the production process. If any faults occur or tolerances are exceeded, the correction values can be used immediately without having to be converted.

Alignment orientation

The key to alignment lies in the working drawing. The workpiece must be aligned according to the dimensions and references specified there.

If no working drawing is available, the elements the workpiece coordinate system refers to are derived from the function elements of the workpiece. These may include e.g. cylinder axes for a transmission, circle segments for a flange or, as shown in the drawing on the left, planes located at right angles to each other.

Alignment procedure

CALYPSO supports "intelligent" alignment, thus taking a lot of work off of the operator’s hands. In most cases, all you have to do is probe certain elements of the workpiece. CALYPSO then determines the necessary information based on this data.

In order to generate a workpiece coordinate system, we must define *three axes* and determine the *zero point* for each of them. This is done according to the following procedure:

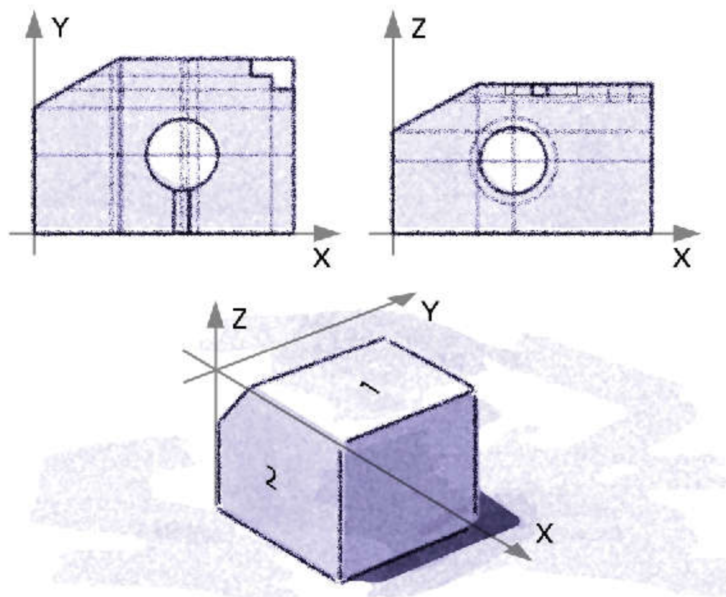
- Probe the 1st element:

  The result is the Z axis (the space axis of the workpiece) and definition of the zero point in the Z axis.
- Probe the 2nd element:

  The result is the X and Y axes and, if applicable, definition of the zero point in the Y axis.
- Probe the 3rd element:

  The result is the final component of the zero point, e.g. in X.

Example no. 1



1st element: 1st axis and zero point
2nd element: 2nd + 3rd axis & zero point
3rd element: zero point

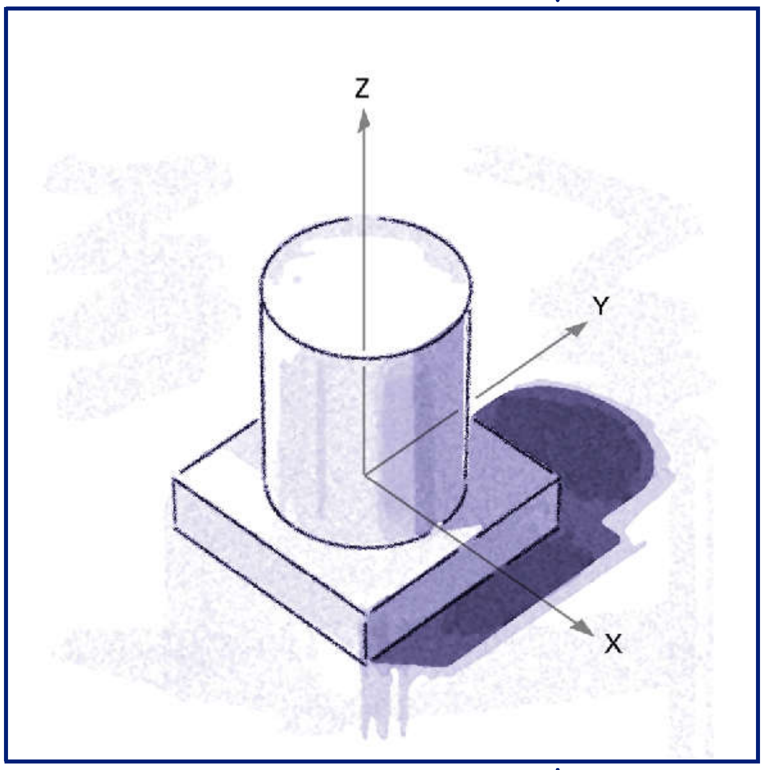
The drawings clearly show the relationship of the specified dimensions. Workpiece planes 1 and 2, which are located at right angles to each other, define the reference axes.

- We start by probing workpiece plane 1. According to DIN (German Industrial Standard) conventions, this first coordinate plane is called the main or *primary reference*. The axis perpendicular to this plane is called the space axis and constitutes the Z axis of the new coordinate system.

  The zero point of the coordinate system is thus defined as a point lying on the specified plane, i.e. is already defined in one coordinate ("first zero point").
- Secondly, we probe workpiece plane 2. The second coordinate plane or *secondary reference* is thus defined. In our case it is the Z-X plane. As a result, we have therefore also automatically defined the second (Y-axis) coordinate of the zero point (the "second zero point").

  With two planes located at right angles to each other, all three axes of a perpendicular coordinate system have thus been defined – only the "third zero point" is now missing.
- Until now, the software only "knows" that the zero point must be located somewhere in the X axis, i.e. along the intersection line of the two workpiece planes. So, in the third step, we probe an element which has the same X value as the desired zero point, e.g. the third, rear workpiece plane or any point located in that plane.

The computer now has all of the required elements and can use the new coordinate system.

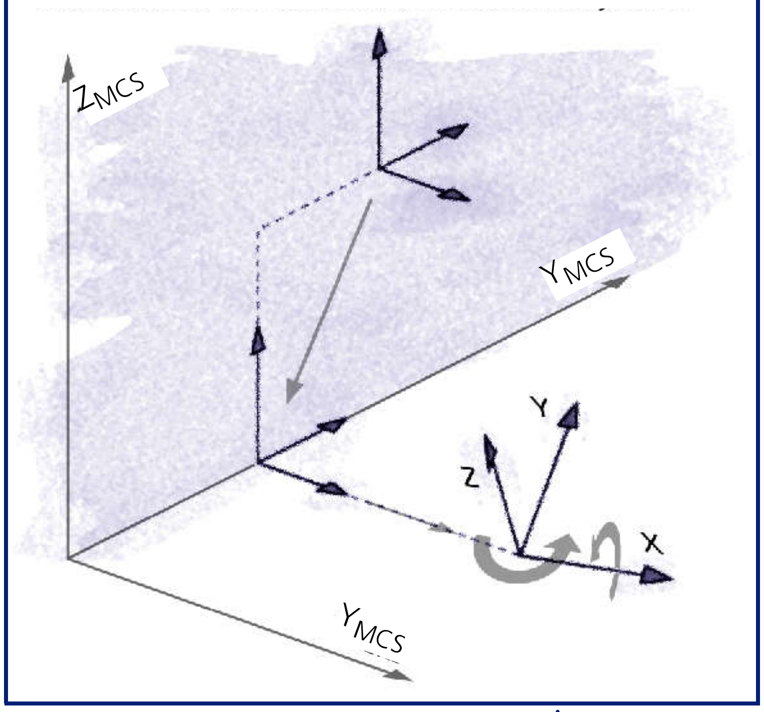


Example no. 2

If we start by probing a cylinder, its longitudinal axis will be the Z axis. The zero point of the coordinate system is thus defined as lying somewhere on the longitudinal axis of the cylinder, i.e. two coordinates have already been determined.

Therefore, two axes but only one coordinate of the zero point still must be defined with the remaining elements.

Displacement of the workpiece coordinate system



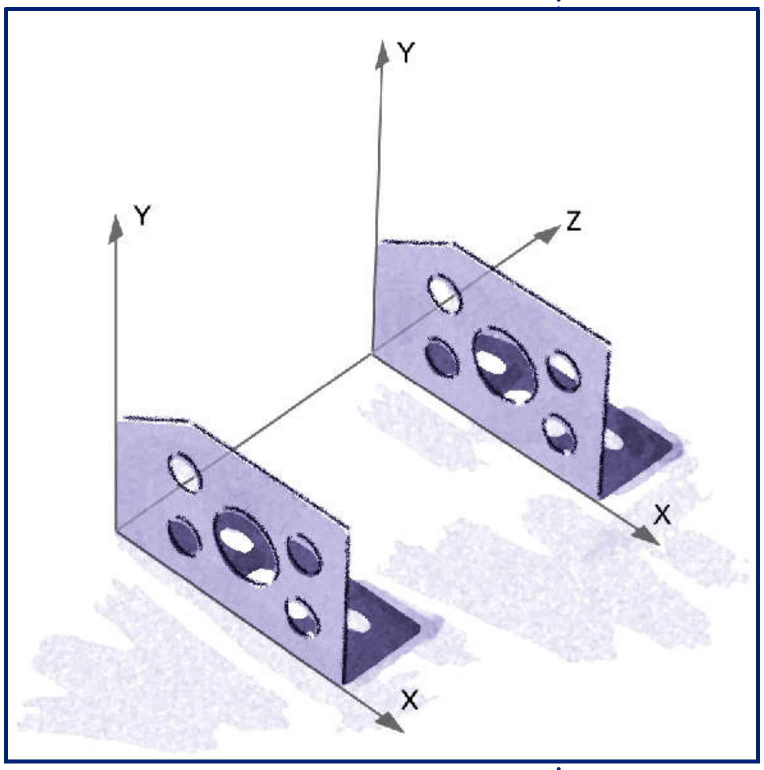
Displacement of the workpiece coordinate system

CALYPSO enables you to watch the zero point in the CAD window as it is displaced from the zero point of the machine coordinate system (MCS) to the new zero point of the workpiece coordinate system (WCS) during alignment.

An example is shown in the drawing on the left:

- First the zero point is parallel-displaced several steps "away from the zero point of the machine coordinate system".
- Then one or more rotations are also performed.

This results in a coordinate system which is aligned to the workpiece and displaced and/or rotated with respect to the machine coordinate system.



Multiple coordinate systems

When measuring larger or more complexly designed workpieces, it may make sense to designate and use not just one, but several different workpiece coordinate systems.

This approach makes it easier for you to measure, print and check certain references to geometric or functionally important elements of the workpiece.

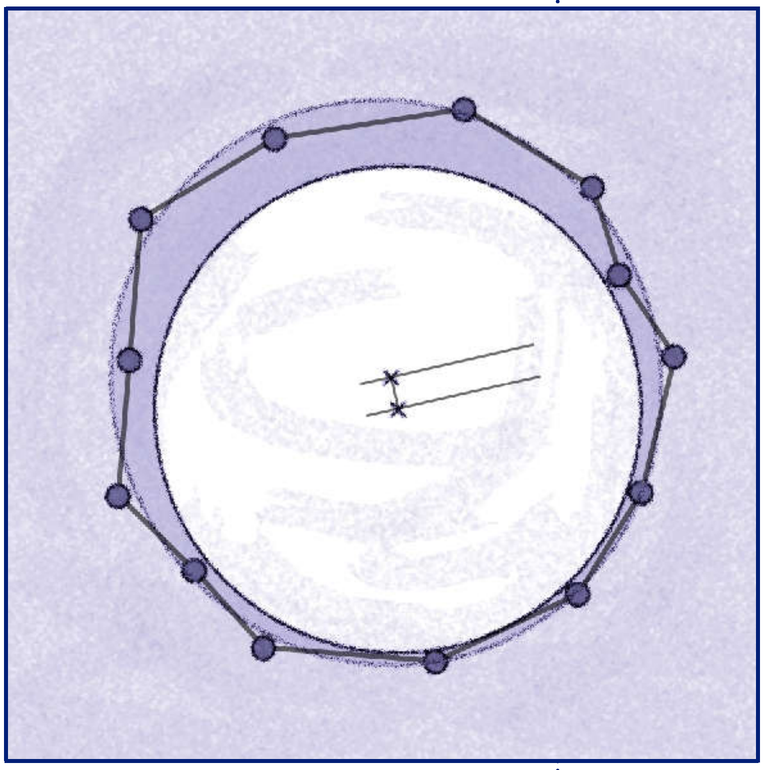
The parallel displacement – or so-called offset – of the workpiece coordinate system by a single vector in one of the coordinate planes is frequently used. This makes sense whenever identical or similar structures repeatedly occur as elements of a single workpiece or the dimensions on the working drawing refer to several different zero points.

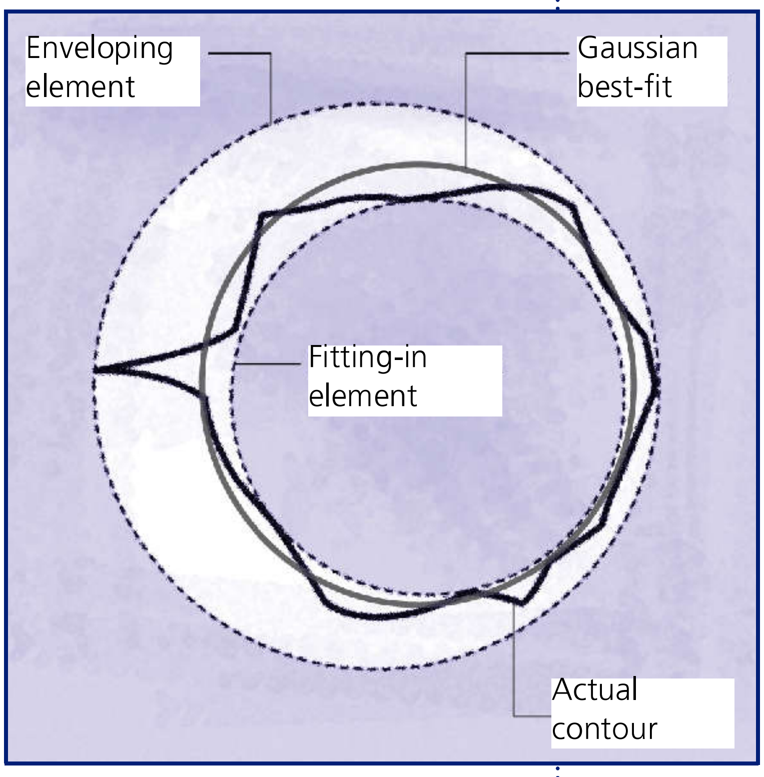
Conversion between different workpiece coordinate systems poses no problem for the measuring software.

Probing strategies

Substitute form

Geometric element of same type as design element best corresponding to measured points. (also called 'substitute element')





In order to obtain meaningful and exact results from your measurements, you should carefully select all probing points. Following the correct procedure will considerably enhance the quality and usefulness of your measurements!

Ideal form and subsitute form

A workpiece is usually designed by combining ideal geometric forms. Thus e.g. a drill hole is defined as a cylinder.

However, a real workpiece deviates from the ideal dimensions, form and position. One of the main reasons for probing the elements is to measure these deviations. The computer then calculates a **substitute form** based on the probing points. This form may deviate in position and size from the design element.

The measured values then provide information on deviations of the workpiece element with regard to its size, position and ideal form.

Automatic element recognition

CALYPSO is able to recognize the type of element being probed after several probings.

How many probing points are required?

The number of defining points is mathematically predetermined for each geometric element. Thus, for example, a line is unambiguously defined by two points and a plane by three points.

All other points of the geometric element are also clearly defined by these points. For this reason, it may be unfavorable to specify an additional point if the point specified does not belong to the element.

For example, if you specify a plane with three points, a randomly selected fourth point will generally *not* be located in the specified plane. And that is the reason why a four-legged chair may sometimes wobble, but a three-legged chair never will.

If we could count on a workpiece containing only ideal geometric elements and only had to measure its size and position, the mathematically specified number of measuring points would always suffice.

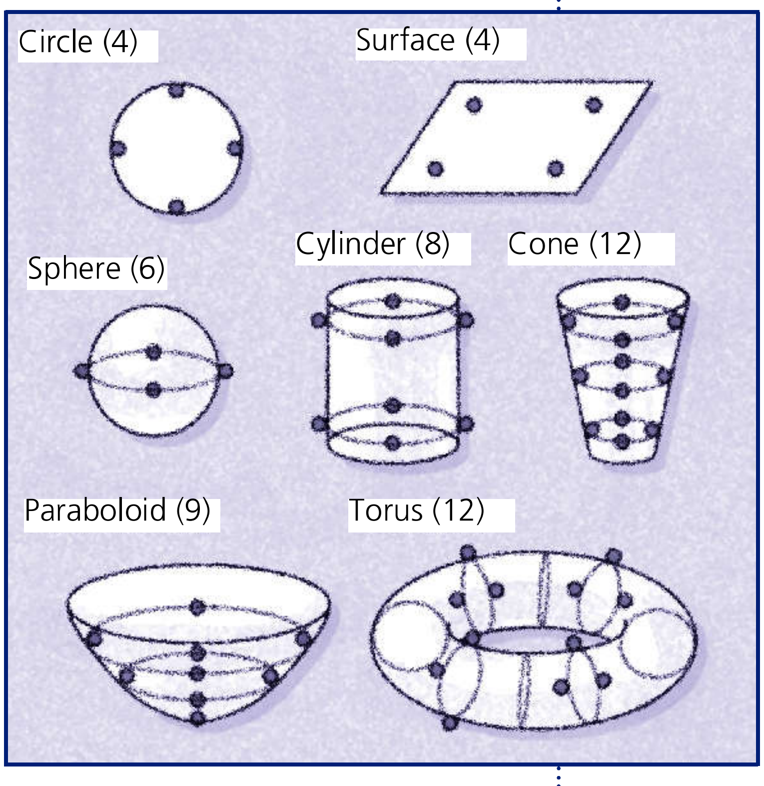
And, for the same reason, the minimum number of points mathematically specified is *not* sufficient to determine a possible deviation of the real workpiece from its ideal geometric form.

The more points you probe, the better the computer can determine the size and position of the ideal geometric substitute element and the more precisely the deviations of the workpiece element from this substitute element can be specified.

On the other hand, since each additional probing also requires more time, some sort of a compromise is called for. The following values have become established in practice:

Element	Theoretical minimum number	Recommended minimum number
Point	1	1
Circle	3	4
Plane	3	4
Sphere	4	6
Cylinder	5	8
Cone	6	12
Paraboloid	6	9
Torus	7	12

Where should the probing points lie?



If a workpiece element had an ideal form, it wouldn't make any difference where the probing points lie – the result would remain the same in any case. However, a real workpiece exhibits production-related deviations and roughness.

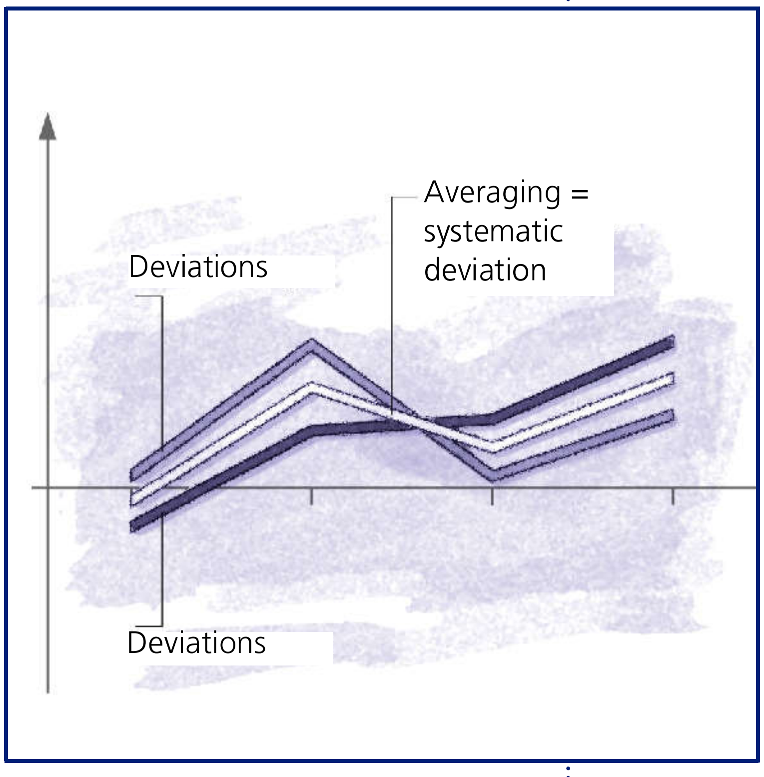
As you can easily see, under these circumstances probing points which are located too close to each other may result in the calculation of very inexact substitute elements due to coincidental errors, burrs or dust particles. This is so because the closer together the probing points are, the more they will be influenced by even the smallest errors or deviations.

It is therefore mathematically verifiable that the most favorable distribution of the probing points is the one in which they are located as far away from each other as possible. For a plane, the probing points should be distributed along the periphery of the surface from which the plane is defined and for a closed form they should be distributed as for a circle, i.e. as evenly as possible.

These considerations form the basis for a *probing strategy*. The latter is used to specify the order in which points on the workpiece will be probed to determine the elements required.

By the way: When automatically processing programmed measuring runs, the computer can change the order of the probing points to optimize its travel paths.

Systematic deviations



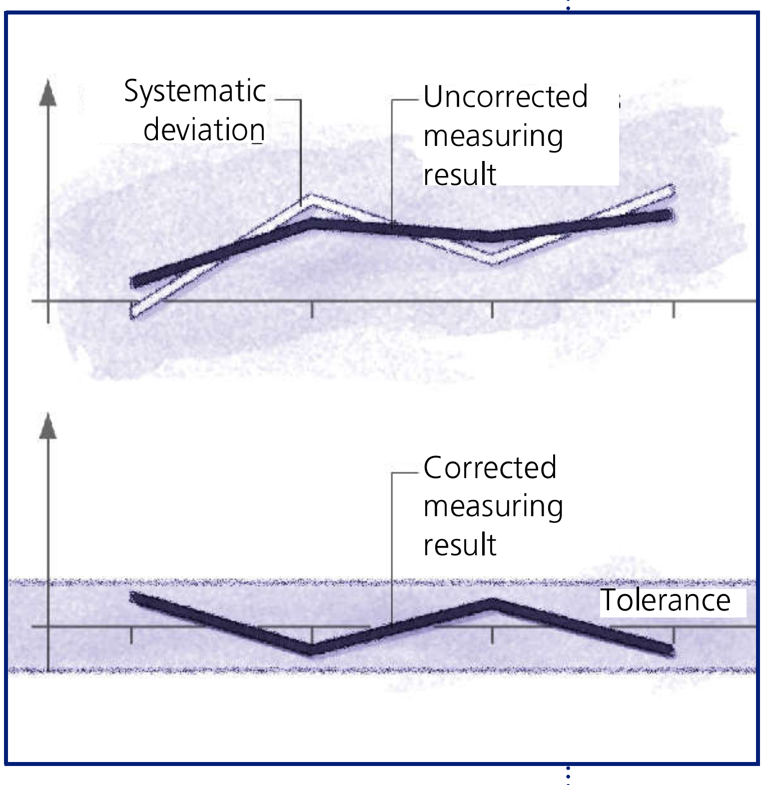
Each measurement results in a value which deviates more or less from the one actually to be measured. This measuring error includes both a *systematic measuring deviation* and a *random measuring deviation*.

The systematic deviation may be caused by inaccuracies of the measuring instrument which

- are production-related (e.g. inaccuracies in the guideways of the granite table) or
- are process-related (e.g. a systematic, minimal sag of a rail caused by the applied weight).

Since the systematic measuring deviation always remains the same under the same conditions, it is also reproducible and therefore correctable.

For this reason, the systematic measuring deviation itself is also to some degree measurable. However a previously precision measured, stable specimen or test piece is required for this purpose. The systematic deviation is then determined by comparing the values measured by the CMM on the test piece with its known measured variables.



Then the deviation thus determined can be input to the computer and used to mathematically correct the values subsequently measured by the CMM. This technique, which is generally referred to as **CAA** (computer aided accuracy), is now generally used in coordinate measuring machines.

The systematic measuring error has largely been eliminated from the data presented for analysis following this correction process.

What you should know now

Which corrections still must be calculated into the measured result after determining the location?

____

____

How is the probe data determined and what must be considered during probe calibration?

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____

How does the computer find out which probe (stylus) is currently probing?

____

____

How is the workpiece mathematically aligned?

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____

What must you consider when planning the probing strategy?

____

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How are systematic deviations compensated for?

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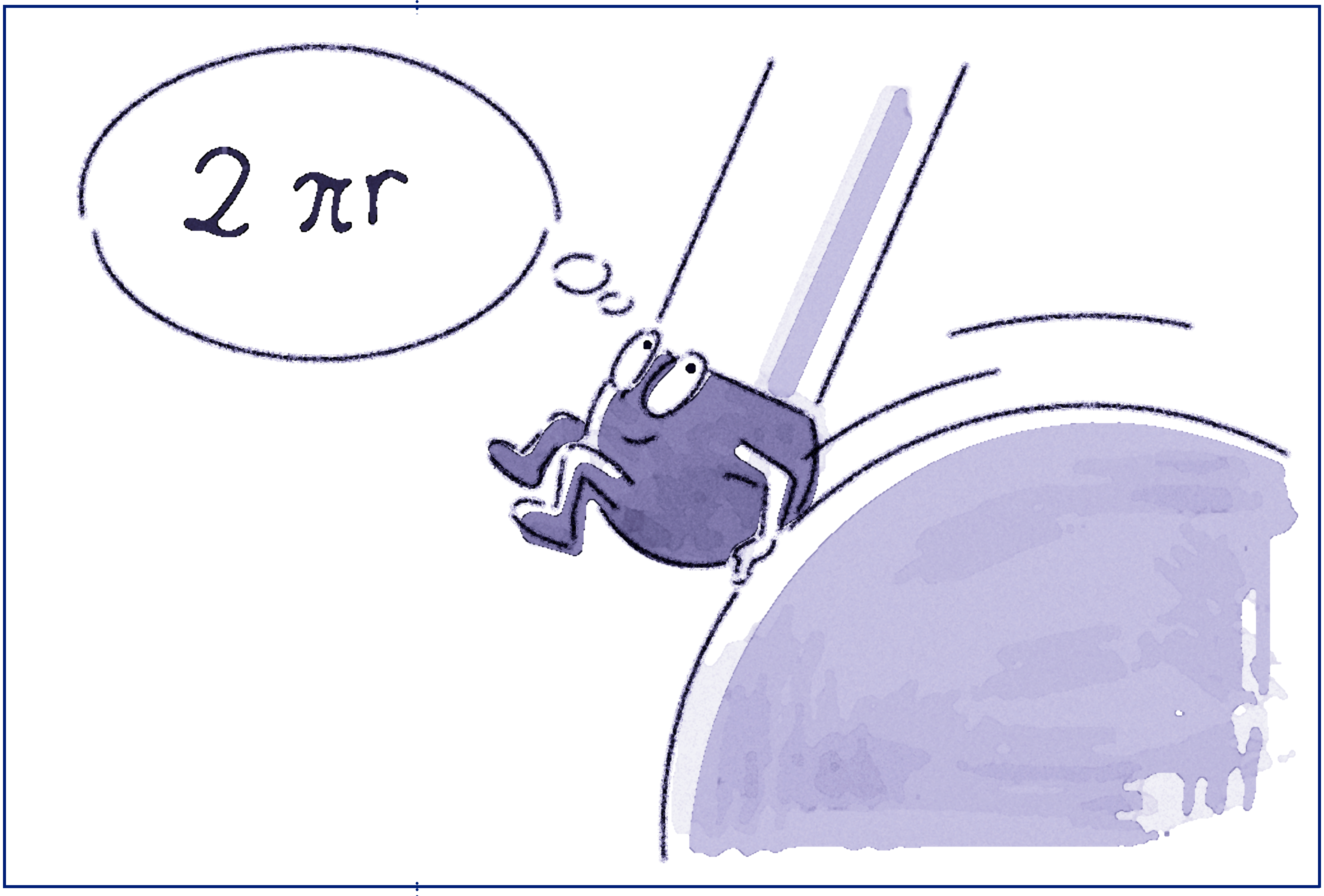
6

What does Calypso actually do?



In this chapter you'll find out what the terms *inspection feature* und *measuring element* mean and how they are used in CALYPSO. We also believe you'll be enthusiastic about the automatic element recognition function .

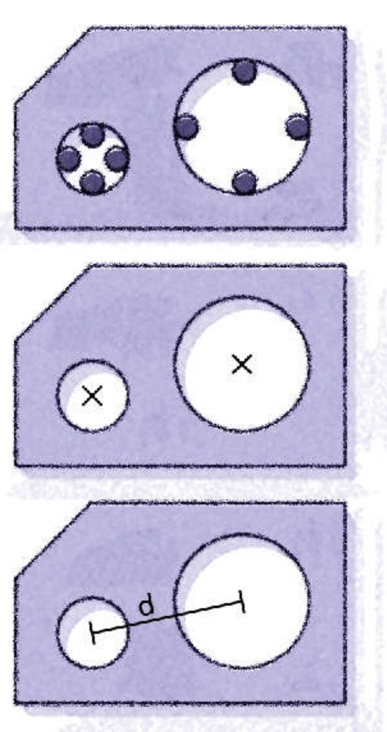
Inspection features and measuring elements

? Inspection feature

An inspection feature is a production or use oriented quality criterion which must be observed and inspected.

? Measuring element

A measuring element is a geometric object whose position and size are determined via probings.



CALYPSO is a sophisticated, convenient and user-friendly software package for operating CMMs and processing measured results.

CALYPSO has an *inspection feature oriented* structure which sets it apart from other user programs.

What does this mean? The measurement is always performed viewing the **inspection feature** as the central criterion.

From inspection feature to probing

The *inspection features,* i.e. the positional tolerance, the dimension and/or some other *features* to be *inspected* – are specified in the drawing.

First you enter all inspection features in a *check plan* which specifies the CNC run. Each of this plan's individual sections deals with a single inspection feature.

Example: The distance between two drill holes as an inspection feature.

The CNC run must include one or more probings for each inspection feature. The inspection features are then determined from the results of the probings.

From probing to inspection feature

Only the **measuring elements** are probed. One or more probing points may be required for each measuring element and one or more drill hole measuring elements may be needed for each inspection feature.

In the example on the left, the two drill holes are measured by probing them. Each drill hole is a measuring element, in this case a *circle*. The center points of these circles and the distance between them are then calculated. The inspection feature is thus generated and compared with the specified value.

What do we see here? The inspection features define the measuring elements, which are then determined by probings. The computer then evaluates the inspection features by linking and calculating the measuring data from the measuring elements.

Automatic element recognition

CALYPSO automatically recognizes most geometric measuring elements as soon as the CMM probes the workpiece. The software uses the information on the positions of the measuring points and the probing directions for this purpose.

For example, if you probe a workpiece at three points CALYPSO will recognize whether the measuring element concerned is a straight line, a plane or a circle based on the position of the points and the probing direction.

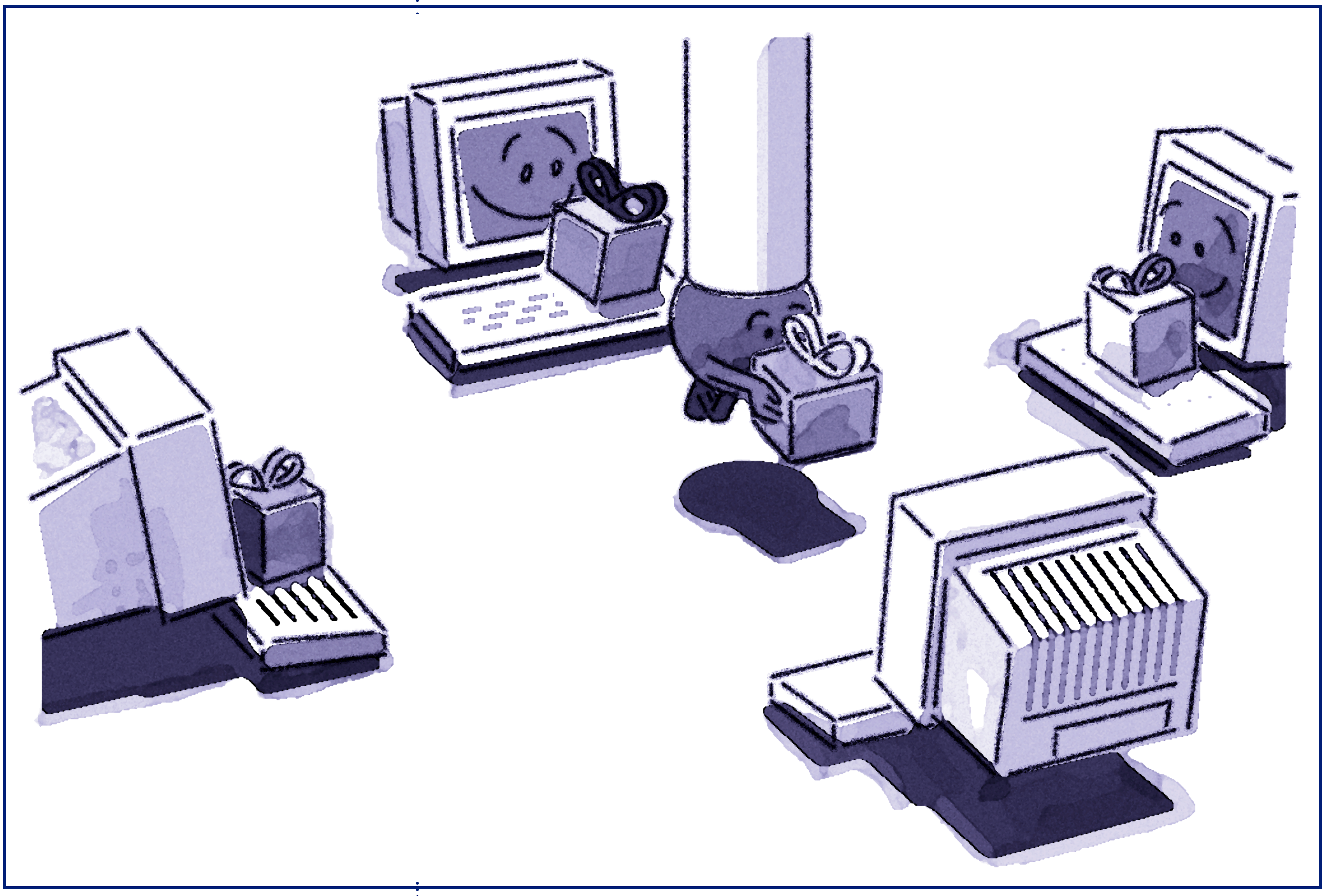
What you should know now

What is an inspection feature? (Give examples.)

How do I obtain measuring elements based on an inspection feature? (Give examples.)

7

From planning to evaluating results – where am I?



Although coordinate metrology offers more accurate and more diverse measuring results, it also requires a carefully considered approach to the work at hand.

This chapter explains various phases of coordinate measuring machine utilization, how they are interrelated, and where they differ.

General survey

Here is a general outline of the procedure for using the coordinate measuring machine and the corresponding software:

Planning (see)

- Inspect drawing / workpiece
- Determine probe configuration
- Determine workpiece clamping
- Determine alignment elements
- Recognize and determine inspection features

Measurement and programming (see)

- Calibrate probes and assign probe storage locations
- Clamp workpiece
- Perform alignment (cuboid safety zone)
- Probe measuring elements
- Add tolerance and nominal size to inspection features
- Define protocol (record) output

Use in production (see)

- Clamp part in fixture
- Calibrate position once
- Start program and let it run
- Clamp new part and execute program run repeatedly

For more information on the individual phases of software utilization in connection with the CMM, please refer to the applicable sections of this chapter.

Survey - working with CAD

CAD

__C__omputer __A__ided __D__esign: the design of workpieces, models, buildings and other objects using a PC with special software.

Test plan

A test plan or check plan is defined in CALYPSO as a sequence of features to be checked via the corresponding measuring elements and other information required for the measurement.

When using **CAD**, you also must create the test plan with CALYPSO. Here is an outline of the correct procedure:

Desk planning stage

- Inspect drawing / workpiece / CAD model
- Determine probe configuration
- Determine workpiece clamping
- Determine alignment elements
- Recognize and determine inspection features

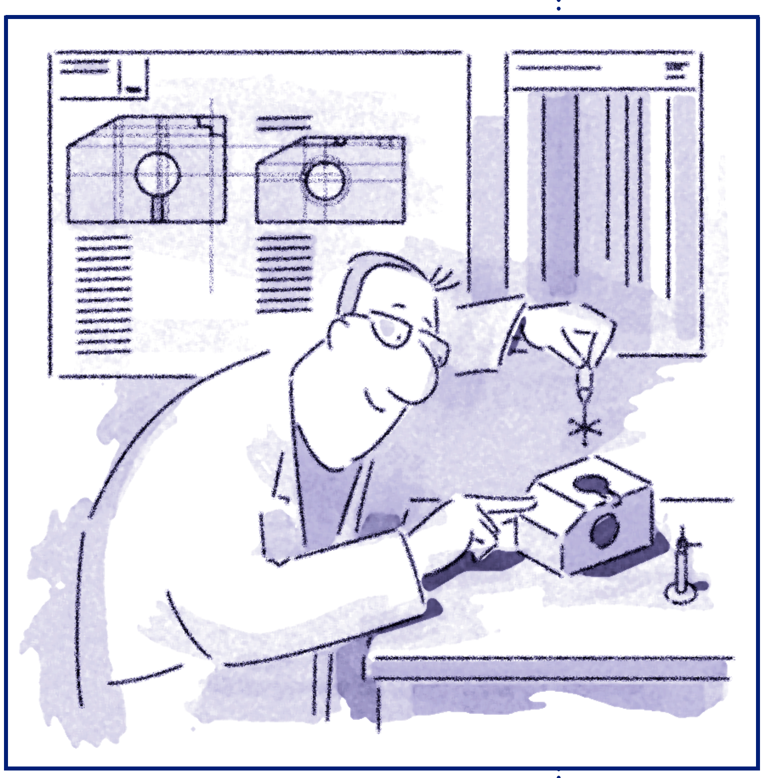
Create test plan on CALYPSO PC

- Enter probe data
- Load CAD model
- Assign elements for alignment
- Define and optimize elements for all inspection features
- Create test plan (= list of inspection features)
- Define evaluation (printer / plot)

Measurement and programming

- Calibrate probes
- Clamp workpiece
- Perform alignment (safety cuboid)
- Start CNC run

Planning



An online computer link saves you, the operator, a lot of time and trouble. Many operations run much easier, faster and more conveniently with a computer. What’s more, you can also perform jobs which otherwise would be difficult or even impossible to accomplish with a computer. These include e.g. the inspection of form and position tolerances.

Still, no computer can ever hope to replace the operator: i.e. it can only perform jobs which you have already planned and programmed.

The appropriate and correct planning of CNC measuring runs is therefore an important prerequisite for useful measuring results.

This should be done as follows:

- Inspect the working drawing
- Determine the alignment and measurement procedure
- Enter procedure in form sheets
- Specify nominal sizes and tolerances
- Select probes

Once you have planned the measuring run, you will also know how you can best obtain which results. Then you can begin the actual programming procedure.

Programming

Based on the plan you have worked out, you can now go on to the next step: programming.

The interconnected coordinate measuring machine and computer can be prepared for the desired job through **part programming**.

How does this work? You simply "walk" the CMM through all of the measuring steps it should automatically perform later on in their correct order.

The coordinate measuring machine thus "learns" what it is supposed to do from you. At the same time, the computer creates and stores a CNC program based on your entries and measuring steps.

Working with CAD

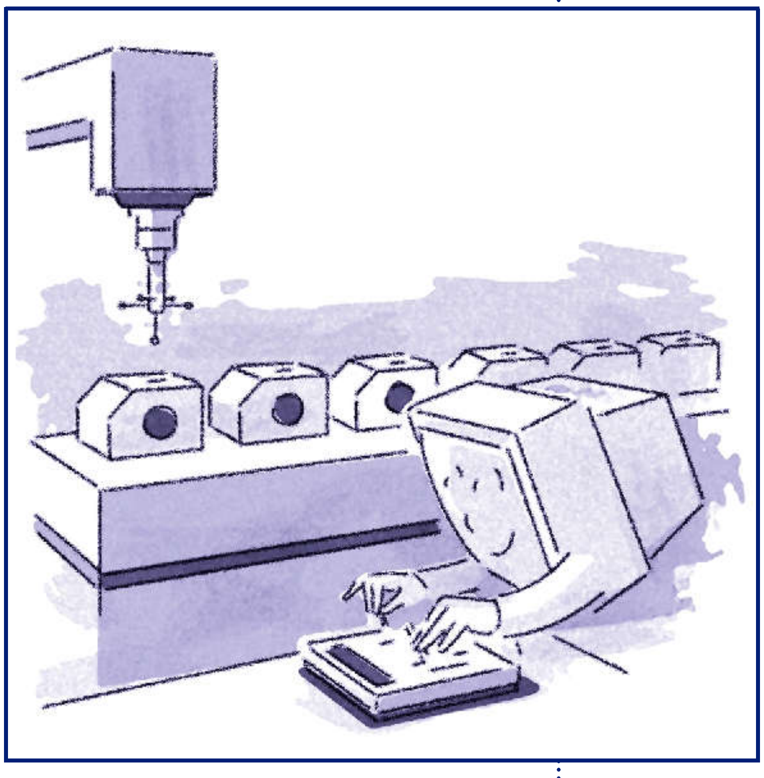
If you work with CAD (see also) and refer to the CAD data as a basis for inspection, you must prepare a **test plan** in CALYPSO prior to programming.

First you must enter the probe data, load the CAD model and enter the elements for the mathematical alignment.

Then you should determine the measuring elements required for all inspection features and enter the inspection features in a list in the correct order. This list constitutes the test plan.

In addition, you can also specify the type of evaluation required.

Use in production



After programming the desired measuring run, you can get down to work:

One workpiece after another is placed on the CMM and the program is started.

While the program is automatically being executed, you can follow its progress on the monitor.

All programmed measuring operations are now processed step by step, but much faster than before. No action is required on your part.

No manual realignment is necessary as long as the workpiece remains clamped in the same position. Precision alignment is also included in the CNC run.

After clamping the workpiece in a different position, you must manually recalibrate its position once. Then you start performing serial measurements again.

Automatic workpiece change

You can use an automatic feeding device to change workpieces. One example of this is pallet measurement, where six identical parts mounted on a pallet are all measured in succession.

Evaluation

All of the data thus acquired is electronically stored by the coordinate measuring machine and documented as required by a connected printer.

Production control

You then evaluate the results of the measurements are and decide what should be done with the workpiece.

If necessary, the correction values are then forwarded directly to the production line to minimize manufacturing deviations.

Additional evaluations

You can output more complex evaluations in various forms: e.g. as mass data, tabular evaluations or graphic displays.

For example, when measuring circles you can graphically display form deviations with a printer.

If a suitable program, e.g. CALYPSO, is installed on your computer, further processing of the acquired data is also possible. For example, you can perform statistical evaluations.

What you should know now

What are the different operating stages and procedures for using a coordinate measuring machine?

How is a coordinate measuring machine programmed?