

Spring 5-31-1993

Coordinate measuring machines : a modern inspection tool in manufacturing

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ABSTRACT

Coordinate Measuring Machines: A Modern Inspection Tool in Manufacturing

by

Matthias Richard Mantel

Coordinate Measuring Machines (CMM) are flexible and universal dimensional measuring devices with the capability for full integration into a CIM information network. Developed as highly precise measuring machines for specially designed measuring rooms, today's CMMs are more and more used in shop floor applications which is a hostile environment for a precise measuring tool. CMMs are offered in a variety of configurations and levels of automation. For the CMM buyer it is therefore essential to have an overview of the different types of CMMs and their subsystems before making a purchasing decision.

To obtain reliable measuring results that are used for controlling and improving manufacturing activities, it is essential to know how accurate the machine can perform and which parameters can influence its performance negatively. The US-standard B89.1.12M-1990 and the German industry guideline VDI/VDE-Richtlinie 2617 for CMM performance testing are compared.

Coordinate measuring technique offers solutions for all dimensional measuring tasks and has replaced most of the conventional measuring tools used in metrology. The most important issues of this technique are discussed in detail in this thesis.

**COORDINATE MEASURING MACHINES:
A MODERN INSPECTION TOOL IN MANUFACTURING**

by
Matthias Richard Mantel

**A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Manufacturing Systems Engineering**

Manufacturing Engineering Division

May 1993

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APPROVAL PAGE

**Coordinate Measuring Machines:
A Modern Inspection Tool in Manufacturing**

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This thesis is dedicated to
my parents
who worked hard their whole life
to enable me my education.
Thank you both !

ACKNOWLEDGMENT

I wish to express my sincere gratitude to my thesis advisor, Professor Joseph E. Kopf and my co-advisor Dr.-Ing. Ernst Hammerschmidt for their guidance, friendship and moral support throughout this thesis.

Special thanks to my academic advisor Dr. Raj S. Sodhi, for his grateful support of my educational stay at NJIT and for serving as a member of the committee.

I further thank Dr.-Ing. Klaus W. Eichner and Dr.-Ing. Ernst Hammerschmidt for their suggestions and support during my work in the CIM-Laboratory at Fachhochschule Darmstadt, Germany in summer '92.

Thanks to the Center of Manufacturing Systems members, Alan Bondhus and Michael Onofrietto, for their suggestions, moral support and timely help.

I also appreciate the work and commitment of all the responsible persons who helped in realizing the exchange program between the universities NJIT (USA) and Fachhochschule Darmstadt (Germany). Special thanks to Joseph E. Kopf, Dr. Raj S. Sodhi, Dr. Gary Thomas, Dr.-Ing. Klaus W. Eichner, Dr.-Ing. Ernst Hammerschmidt, Bernd Wächter, Ellen Göbel and Christoph Heberer.

And finally, a thank you to my friend Sue for her help, understanding and patience in the past few months.

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CHAPTER 1

INTRODUCTION

Dimensional inspection of industrial parts is an activity with increasing importance in the manufacturing process. Part tolerances, once quoted in fractional figures, are now quoted in thousandths of a millimeter. This trend and the demand for a universal, flexible and precise inspection device, which could provide full capability for integration, in the vision of Computer Integrated Manufacturing (CIM), accelerated the goal oriented development process of Coordinate Measuring Machines (CMM) in the past twenty years. From today's point of view, the introduction of coordinate measuring technique, later especially the CNC-Coordinate Measuring Machines, into dimensional metrology can be seen as revolutionary as the introduction of the Numeric Controlled (NC)-machining technique in manufacturing.

CMMs were first introduced as manual measuring devices in the early 1960's, and were based on three-axes machining tools where the tool was simply replaced by a sensing device. The sensors employed at this time were hard probes which made contact with the part surface. The center coordinates of the hard probe were shown on a display and recorded by the operator. These measurements were very time consuming, with limited accuracy and repeatability and with the chance of user errors. In 1972, the first CMM which satisfies today's definition of a CMM by observation of the principle of coordinate measuring technique, was built by the manufacturer C. Zeiss in Germany. After this breakthrough the CMM evolution accelerated, especially in the field of development of new probing systems.

Touch trigger contact probes were developed first which overcame the disadvantages of hard probes and made it possible to automate the process of making contact. In 1973, measurement accuracy reached a new level due to the introduction of a three-dimensional measuring probe system. Today non-contact probe systems, like laser devices or electronic cameras are present, which enlarge the spectrum of probe systems from which the user can choose.

The CMM development process was and is still driven strongly by the very fast expanding computer technology. In the early stage, the operator had to record and to process the data manually. Today the computer takes over these tasks and opens new horizons for measurements and their evaluations. Special software programs are written to solve even very difficult and complex measurement tasks like measurement of gears, turbine blades or free-form shaped parts in the automobile industry. Manual controlled measurements have become computer controlled, whereby once the measuring run is programmed, it can be repeated for a whole series of parts without any additional effort. Traditional Tech-in programming is the method used for programming computer controlled CMMs, by writing the code in a system specific programming language and then leading the probe system around the measuring object for measuring. This is a very time consuming and operator specific process during which the machine cannot be used for productive part measurements. To overcome these disadvantages and in order to integrate the island of automation, CMM, into the CIM information flow by sharing data with a Computer-Aided-Design (CAD) system, various interface formats are used to exchange data. The newest development in this direction is the Dimensional Measurement Interchange

Specification (DMIS), through which CAD-data are used to write a CMM program in a neutral format which can then be downloaded to CMMs of different manufacturers.

CMMs were first developed as inspection machines for use in special measuring rooms under a controlled and stable environment. However, the users demanded a CMM which could be used on the shop floor, in a hostile environment, next to the production machines as a highly precise measuring tool to decrease the inspection lead-time. The CMM-manufacturers tackled this challenge and are today able to offer machines which are hardened against environmental influences with a reasonable accuracy for this kind of application.

CHAPTER 2

COORDINATE MEASURING TECHNIQUE

2.1 Description of the Object Shape

The object shape of an industrial part, which is called the part surface, is built by the summation of all its partial boundary areas. For further understanding and notational distinguishing it is necessary to first define the following terms.

- *Nominal Shape*
- *Actual Shape*
- *Substitute Shape*

The *Nominal Shape* is the geometric ideal shape of a part, given by the dimensions on the blueprint or derived from the numeric data from a CAD-system. This shape consists of individual ideal geometric elements.

The *Actual Shape* is the shape that is manufactured and which separates the part from its surrounding medium. It contains more or less extensive deviations from the nominal shape. Every single geometric element contains dimensional deviations because of manufacturing tolerances. The actual shape consists of boundary areas, edges and corners. Actual object edges and corners cannot be measured through the touch of a physical device.

The *Substitute Shape* is the shape which is built by ideal geometric elements from individual measured points on the surface of the part. These geometric elements which substitute the actual geometric elements are used

to evaluate the dimensional accuracy through comparison with the nominal geometric elements. Figure 2.1 illustrates the difference between the above defined types of object shapes based on a simple object.

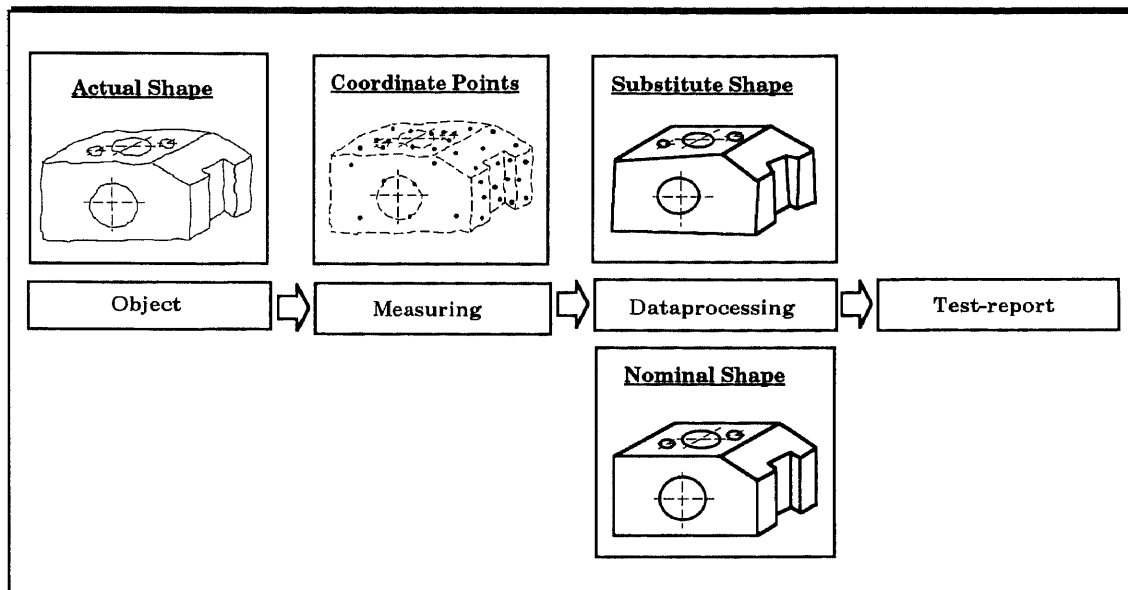


Figure 2.1 The Principle of Coordinate Measuring Technique

2.2 The Principle of Coordinate Measuring Technique

The actual shape of a part is registered by points based on a coordinate system by measuring individual points on the object surface with a probe system. From the registered coordinate points a numerical model of the part is generated. The numeric model of the part is a substitute of the actual part shape consisting of basic geometric elements like circles, planes, cylinders, etc. The calculation of these geometric elements is based only on the touched points. The area in between these points is not taken into consideration for calculating the elements. To calculate a geometric element a mathematical minimum number of points is required. When more points are taken, a better fitting element can be calculated by a mathematical approximation method,

such as the mathematical models explained in section 2.3.2. To evaluate the dimensional accuracy of a part, the substitute shape is compared with the given nominal shape and the results of this comparison are documented in a test report. Figure 2.1 illustrates the principle of coordinate measuring technique.

2.3 Mathematical Fundamentals

2.3.1 Geometric Elements

The majority of industrial parts are described as the summation of a few basic geometric elements. In order to solve measuring tasks by using coordinate measuring technique it is necessary to calculate the geometric features of the object based on the measured coordinates. If the actual shape would be geometrically ideal, it would be sufficient to calculate the substitute elements with only the mathematical minimum number of points (*Actual Element = Substitute Element = Nominal Element*). The mathematical minimum number of points is equal to the degrees of freedom of the geometric element. It is generally known that manufactured parts are not geometrically ideal, and therefore, the minimum number of points is not sufficient to describe the actual element. Generally, the more points that are taken from the actual element to calculate the substitute element the better the representation is. Economical reasons make it impractical to take a large number of points, and after a certain number of points have been taken, the accuracy of the result reaches a threshold. A metrological minimum number of points and their distribution over the element is advised for calculating the geometric elements (Table 1) [41,70].

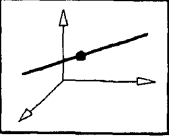
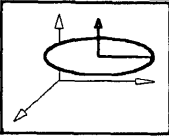
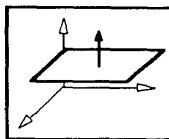
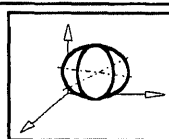
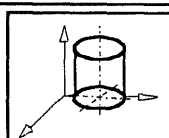
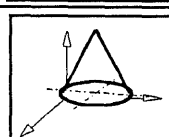
Geometric Element	Mathematical Minimum Number	Metrological Minimum Number
 Line	2	3
 Circle	3	4
 Plane	3	4
 Sphere	4	6
 Cylinder	5	8
 Cone	6	12

Table 1 Minimum Number of Points in Coordinate Measuring Technique [41]

As written in [41] the four basic elements used in coordinate measuring technique are:

- *Plane*
- *Cylinder*
- *Sphere*
- *Cone*

All of these elements are three dimensional elements that represent surfaces which can be physically touched by a stylus. However, to make simplified measurements possible, two other geometric elements which comprise edges on the objects and therefore cannot be touched with a stylus, are in use:

- *Line*
- *Circle*

These two elements have to be used carefully and with some knowledge as shown in the example of a circle in [41]. In order to measure a bore by measuring a circle the stylus has to be guided exactly in one plane that is exactly perpendicular to the bore's axis, otherwise an ellipse will be measured as Figure 2.2 shows.

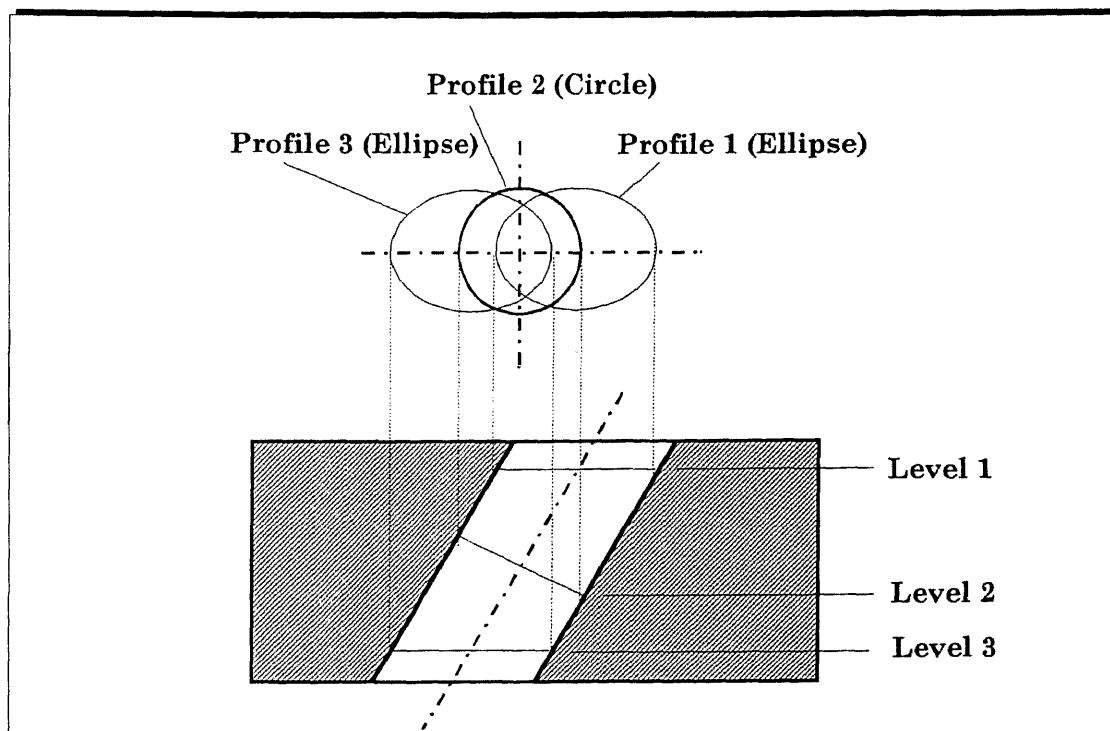


Figure 2.2 Mistakes in Measuring a Circle [41].

If the measuring task is to determine the bore diameter and location, it is very critical if there is only one circle being measured. A correct result can be assured if a cylinder and a plane is measured to solve this problem. The cylinder's diameter represents then the bore diameter and the bore location can be determined by the intersection point of the cylinder axis with the plane.

For planning the measurements, it is always helpful to remember that a CMM is a three-dimensional measuring tool. Therefore, a measuring task should be solved by measuring three-dimensional elements. The price of increased measuring accuracy is paid for by a bigger measuring effort, since more points need to be measured and more calculation time is required for three-dimensional element measurements. The equations and solution algorithms for solving the basic geometric elements used in coordinate measuring technique according to the German Industry Standard 32880 (DIN 32880) can be found in [14,41].

2.3.2 Mathematical Approximation Techniques

When the geometric elements are measured with more points than their mathematical minimum number of points, as described in section 2.3.1, a mathematical approximation technique has to be applied to calculate an approximated ideal element from all the measured points. There are different approximation techniques available to do this and every technique applied to the same set of points can yield a different result. Each technique should be selected based on their specific characteristics based on functional needs and used with the knowledge that some information about the actual shape will be lost after an approximation method is applied (Figure 2.3) [65].

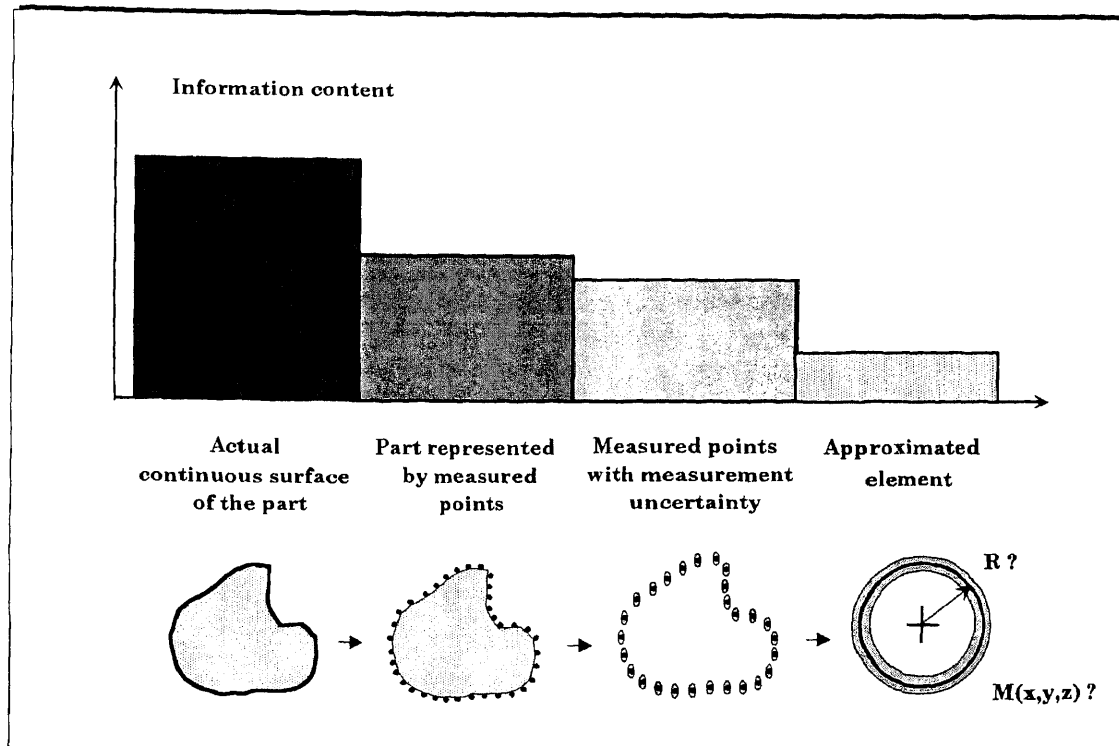


Figure 2.3 Loss of Information through Approximation of an Object Surface Measured by Single Points [65]

The four approximation techniques listed below are commonly used in the coordinate measuring technique, and their differences can be visualized as in Figure 2.4 :

- *Least Squared Sums (Gauss Criterion)*
- *Tschebyscheff Minimum Criterion*
- *Maximum Contact Element*
- *Minimum Contact Element*

The *Least Squared Sums* is the standard approximation technique used by the CMM manufacturer software to approximate geometric elements. This method, developed by the statistician Gauss, determines a mean element by minimizing the squared distances of all the points to the mean element. It assigns all the points equal statistical weights.

$$\sum d_i^2 = \min. \quad (2.1)$$

The *Tschebyscheff Minimum Criterion* minimizes the largest distance between two elements of equal shape. For the first element only the minimum number of points is taken into account, whereas for the second element only one point is needed to determine its location. This method is specified in the international standard ISO 1101 and used for evaluating form deviations. Outliers caused by dirt or scratches have to be considered carefully in order not to falsify the results.

$$\max. (|d_i|, i = 1, \dots, n) = \min. \quad (2.2)$$

The *Maximum Contact Element* is the element with the smallest dimensions that includes all the measured points. It is used for example to evaluate the diameter of a shaft for a system of fit.

$$R_{\max.} = \min. \wedge d_i \geq 0 ; i = [1, n] \quad (2.3)$$

The *Minimum Contact Element* is the largest possible element which lies fully inside all the measured points. It is applied to evaluate the largest inside diameter of a bore hole for a system of fit.

$$R_{\min.} = \max. \wedge d_i \leq 0 ; i = [1, n] \quad (2.4)$$

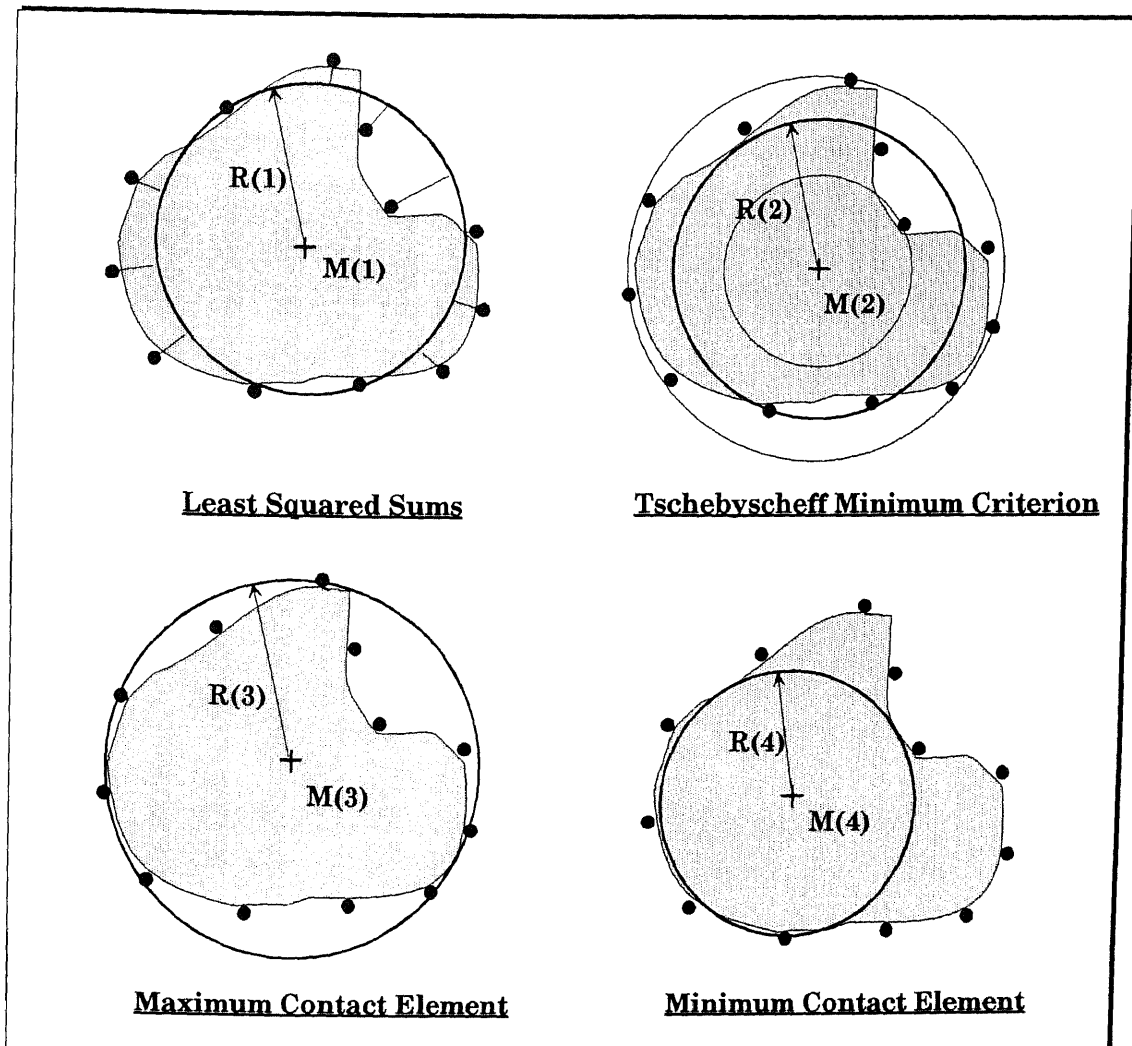


Figure 2.4 Different Approximation Techniques for the Example of a Circle [65].

2.3.3 Coordinate Systems

By using coordinate measuring technique an object is measured by points on its surface. For determination of the point location, a measured point has to be related to a reference system, which is called the coordinate system. The Coordinate Measuring Machine's linear measurement transducers, which are mounted to the axes of travel, embody such a reference system which is known as the *machine coordinate system*.

The objects to be measured cannot be exactly aligned to this machine coordinate system, and therefore the exact object location and alignment in the machine's work envelope has to be determined before measurements can be made. On CMMs, the part alignment in its work envelope is done mathematically by a computer by measuring a few geometric elements on the object itself. The mathematical alignment of the object is one of the most cost saving points and a very important advantage of CMMs compared to conventional measurement devices, where the part alignment is done by mechanical fixtures. The mechanical fixtures are mostly complex and very expensive single purpose devices, with manufacturing tolerances itself that contribute to the measurement uncertainty of conventional measuring devices. A part related reference system, also known as the *part coordinate system*, is created by aligning the object. This coordinate system is related to the machine coordinate system through the following mathematical equation:

$$\begin{matrix} \rightarrow \\ \mathbf{X} \\ \text{Part} \end{matrix} = \mathfrak{R} * \begin{matrix} \rightarrow \\ \mathbf{X} \\ \text{Machine} \end{matrix} + \begin{matrix} \rightarrow \\ \mathbf{T} \end{matrix} \quad (2.5)$$

where: \mathfrak{R} is the matrix of rotation and \mathbf{T} the translation vector

The mathematical alignment of a part in the machine coordinate system can usually be done in numerous ways by measuring various elements. It is a very important part of the measurement on a CMM and has to be done very carefully with full knowledge of the underlying principles. In general it can be said, that the errors made in the part alignment process

directly influence the measured results. A general rule for aligning an object cannot be given, and therefore the method and the elements used for the alignment are decided on and defined for each measuring task individually. For prismatic objects, the international standard ISO 5459 and the German standard DIN 32 880 [16] recommend the *Three-Plane-Method* to carry out the part alignment. This method is illustrated in Figure 2.5 and described as follows. The normal vector of the primary plane, which levels the part and gives the main direction of the coordinate system, should be chosen as the element with the tightest manufacturing tolerances when applicable. The secondary direction is perpendicular to the main direction and is a result of the intersection of the secondary plane with the primary plane. The origin of the part coordinate system is the intersection point of all the three planes.

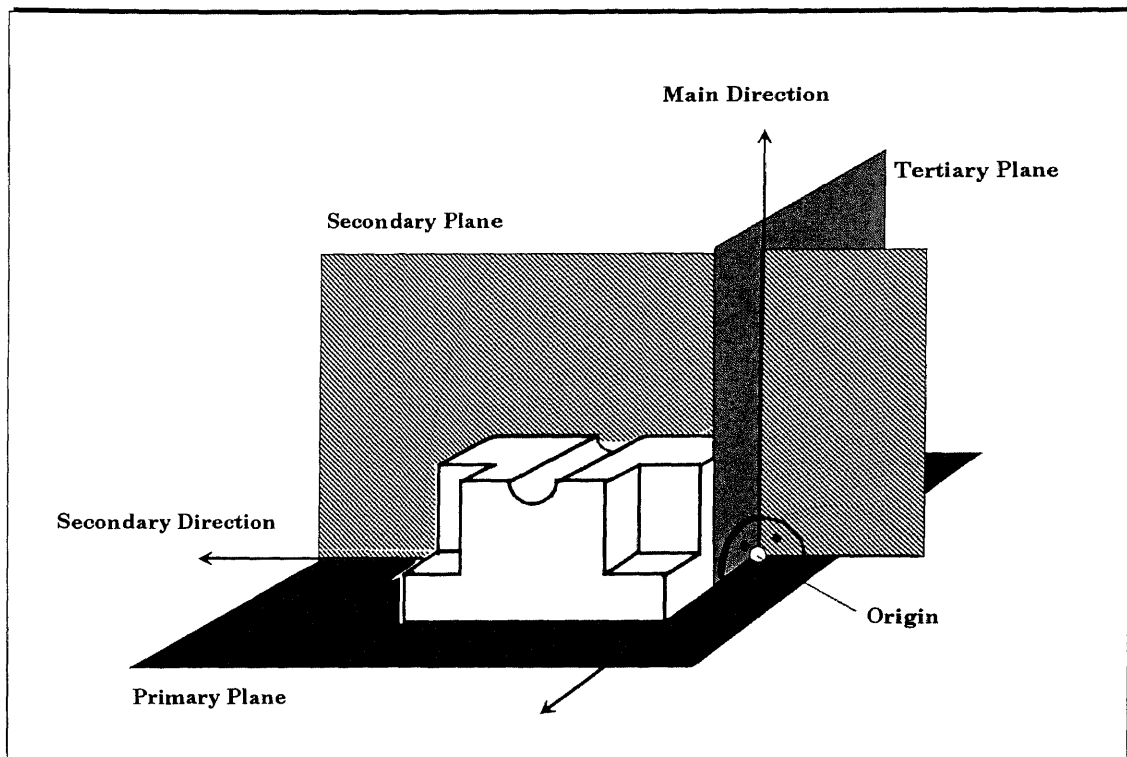


Figure 2.5 The Three-Plane-Method to Create a Coordinate System According to ISO 5459 and DIN 32880

Up to now a three-dimensional cartesian coordinate system was assumed for the previous descriptions without being mentioned explicitly. This type of coordinate system, where all the three directions are perpendicular, is the type which is most commonly applied in measurements on CMMs, because the machine structure itself is built most often like such a coordinate system. Nevertheless, in coordinate measuring technique a few other coordinate systems, which might be useful in one or another application or useful for reporting the results, are used. The transformations of single points and elements between the different types of coordinate systems can be done by using mathematical equations with a computer if the software is available. The four types of coordinate systems employed in coordinate measuring technique are (Figure 2.6) :

- *Cartesian Coordinate System*
- *Polar Coordinate System*
- *Cylindrical Coordinate System*
- *Spherical Coordinate System*

2.3.4 Stylus Radius Compensation

In coordinate measuring technique the part surface is probed with a mechanical stylus which usually employs a sphere as the contact element. The coordinates of the points registered determine the center location of the stylus in the coordinate system. However, the center location of the stylus is not identical to the contact point with the part surface and therefore the radius of the contact element has to be compensated for, otherwise wrong dimensions might be recorded (Figure 2.7).

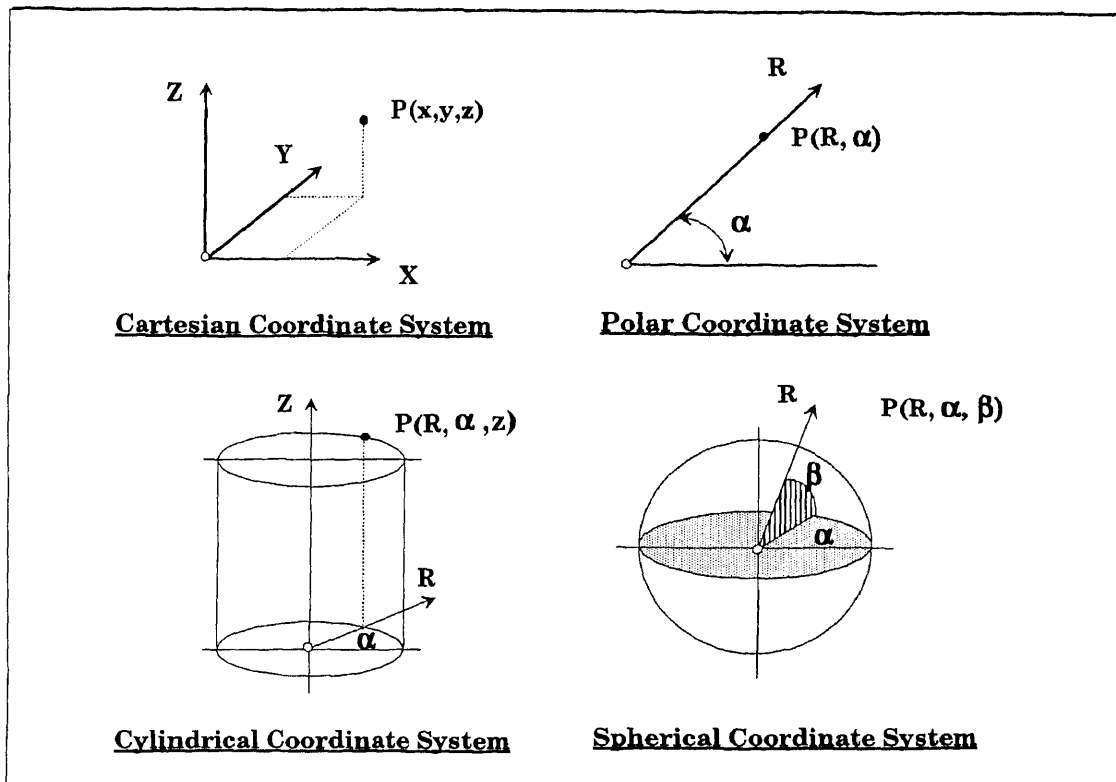


Figure 2.6 The Different Types of Coordinate Systems

The radius compensation for the basic geometric elements is done in two steps. In the first step, the approximated geometric element is calculated with the stylus center locations and then as the second step the geometric element is radius compensated, by simply adding or subtracting the stylus radius or its diameter (Figure 2.7).

In discussing the radius compensation, so far only the radius is taken into account, however the question in which direction the radius should be compensated, is of importance and will be discussed below.

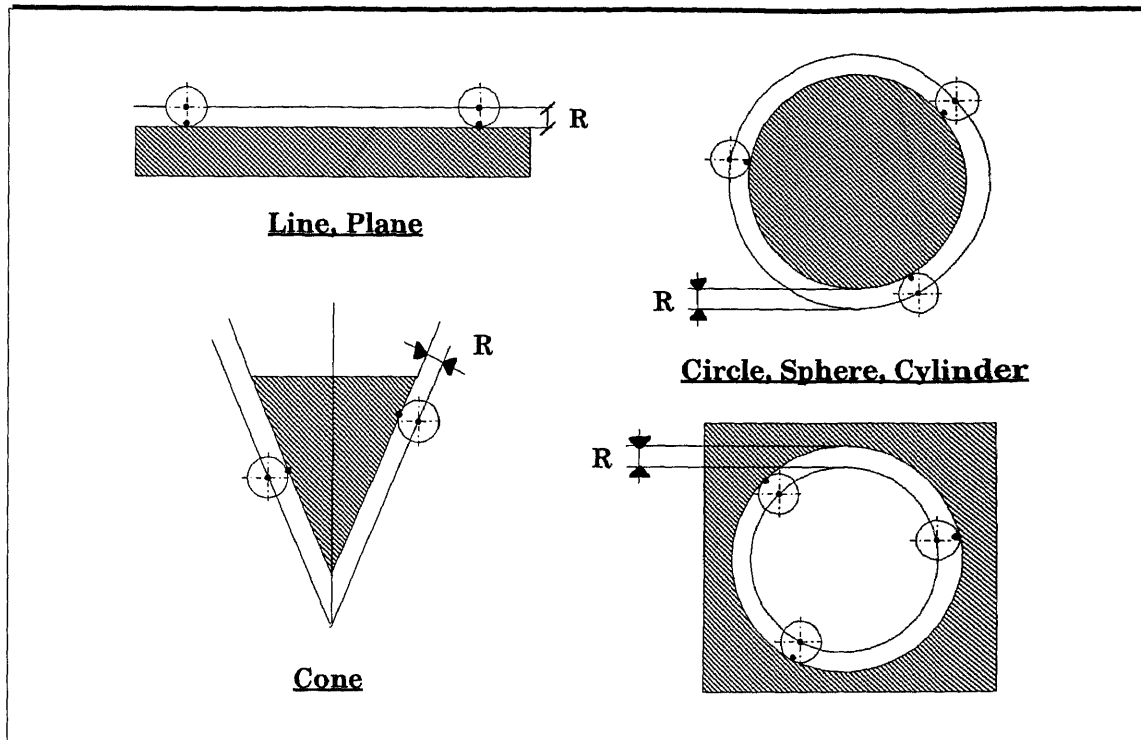


Figure 2.7 Radius Compensation for the Basic Geometric Elements [41].

Two possible compensating directions are usually considered, as illustrated in Figure 2.8:

1. *Compensation of the stylus radius in the direction of the normal vector at the probing point.*

This is the only absolute correct compensation direction.

2. *Compensation of the stylus radius in a direction parallel to one of the coordinate system axis.*

As Figure 2.8 illustrates, this method can lead to an error, also known as the cosine error. When using this method the part should be aligned to the machine coordinate axis, to keep the cosine error as small as possible.

If a CMM is equipped with a contact probing system, it is essential to know and to investigate before the measurements are planned which compensation methods are available for that particular machine, which is dependent on the machine's capabilities.

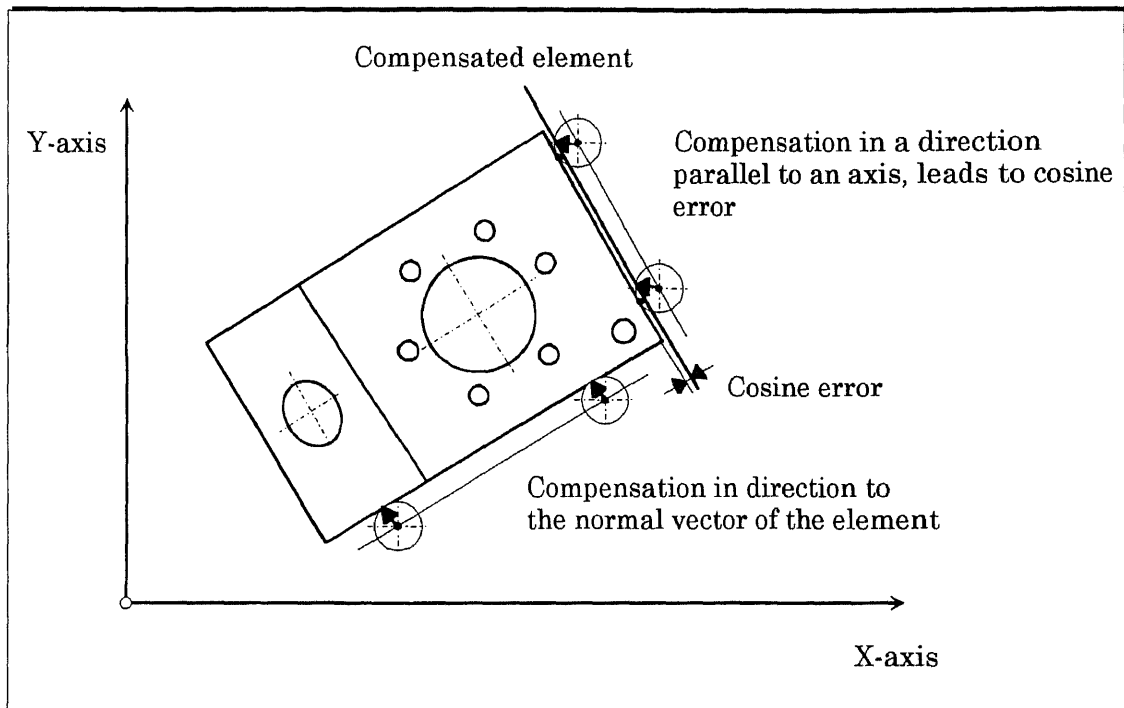


Figure 2.8 The Influence of Different Compensation Directions

CHAPTER 3

COORDINATE MEASURING MACHINES

3.1 Machine Configurations

Coordinate Measuring Machines are available in a variety of configurations. Each configuration has advantages which make that particular CMM suitable for certain applications. The variety of CMM configurations can be classified in four primary types of configurations (Figure 3.1):

- *Cantilever*
- *Bridge*
- *Gantry*
- *Horizontal Arm*

Cantilever-type Coordinate Measuring Machines are usually the smallest in size and occupy a minimum of floor space. This configuration permits a completely unobstructed work area, allowing full access to load, inspect and unload a part that might be larger than the table itself. On the other hand, the single overhanging beam support for the probe head may limit the accuracy if a special compensation is not built into the cantilever arm [68].

Bridge-type Coordinate Measuring Machines are built as moving bridge or moving table models and represent the most popular type of configuration comprising approximately 90% of CMM sales. The double-sided support of this type of CMM provides more support for large and medium-

sized machines, and makes the machine very stiff so that the measuring uncertainty is less. However, accessibility to the work area is limited by the bridge and parts larger than the clearance of the bridge cannot be measured.

Gantry-type Coordinate Measuring Machines are the largest CMMs available on the CMM market and are usually made according to customer needs. The size of the work area can reach up to 20 m x 6 m x 4 m. This size might be needed to measure parts like airplane wings, automobile bodies, ship propellers or large diesel engines. The accessibility to the work area can be limited by columns on which the rails for the cross beam are mounted. The weight of the parts being measured is usually out of focus because they are not placed on the machine itself. Instead the focus lies more on a proper foundation of the machine base which should be isolated from the buildings remaining foundation. The measuring accuracy can be classified as medium.

Horizontal arm-type Coordinate Measuring Machine is the only type of CMM where the probe head is mounted to the horizontal y-axis instead of being vertically mounted to a ram (z-axis). For some applications a horizontal access might be desirable for parts which are machined on horizontal machining centers. This type of CMM has a very good accessibility to the working area from all sides and is substantially less restricted to part sizes being measured. The measuring speed can be high because the moving masses are lighter. This type of CMM configuration achieves less accuracy because of machine structure deformation.

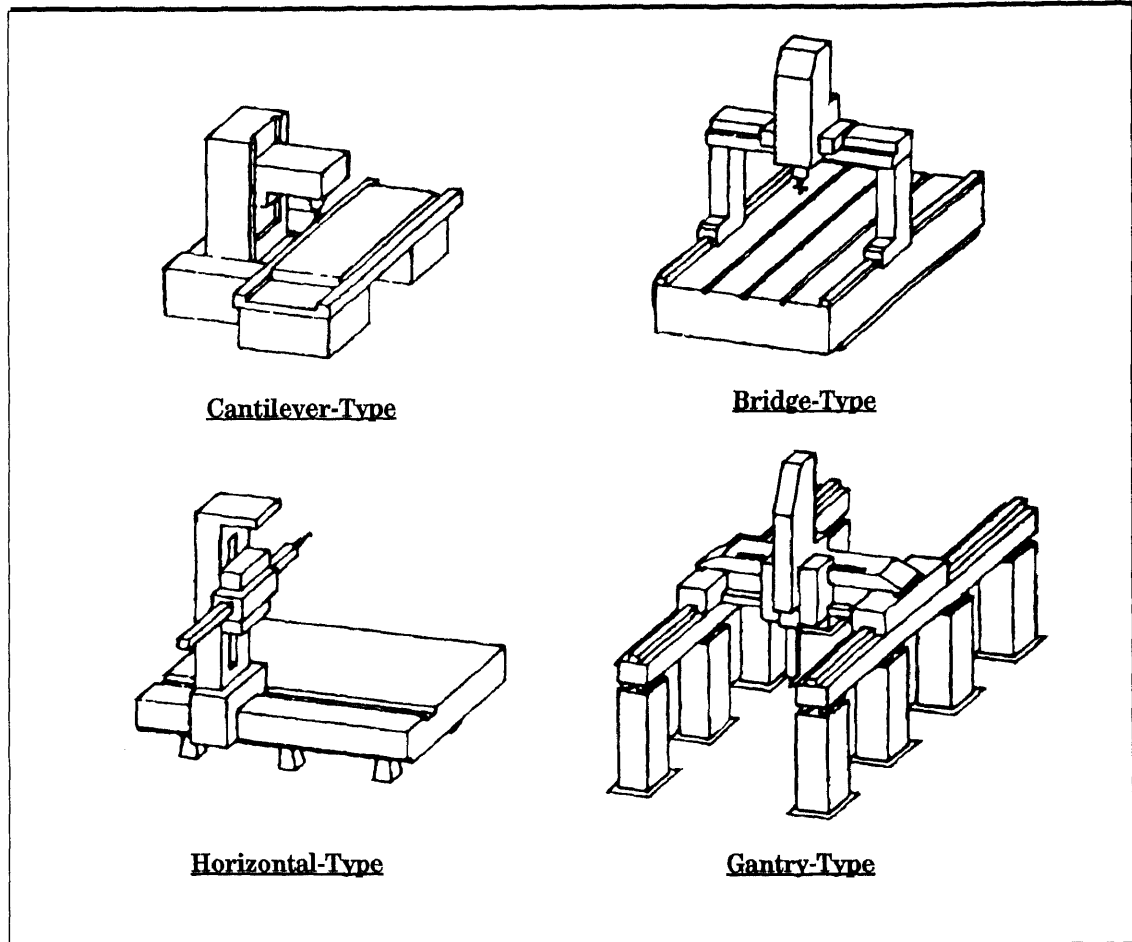


Figure 3.1 The four primary types of CMM configurations [32]

3.2 CMM Components

A Coordinate Measuring Machine consists of basically four major functional components that can be developed differently depending on the CMM's configuration, on the type of probe system and the level of automation. The four primary CMM components are (Figure 3.2):

- *Machine Structure*
- *Linear Measurement Transducers*
- *Probe System*
- *Computer Hardware and Software*

For a CMM buyer it is virtually impossible to select the appropriate CMM without carefully evaluating the single system components needed for today's and future applications. Therefore, the available system components are specified and the more frequently used subsystems are described in detail in the following sections to give a potential CMM buyer an overview of the function of each subsystem.

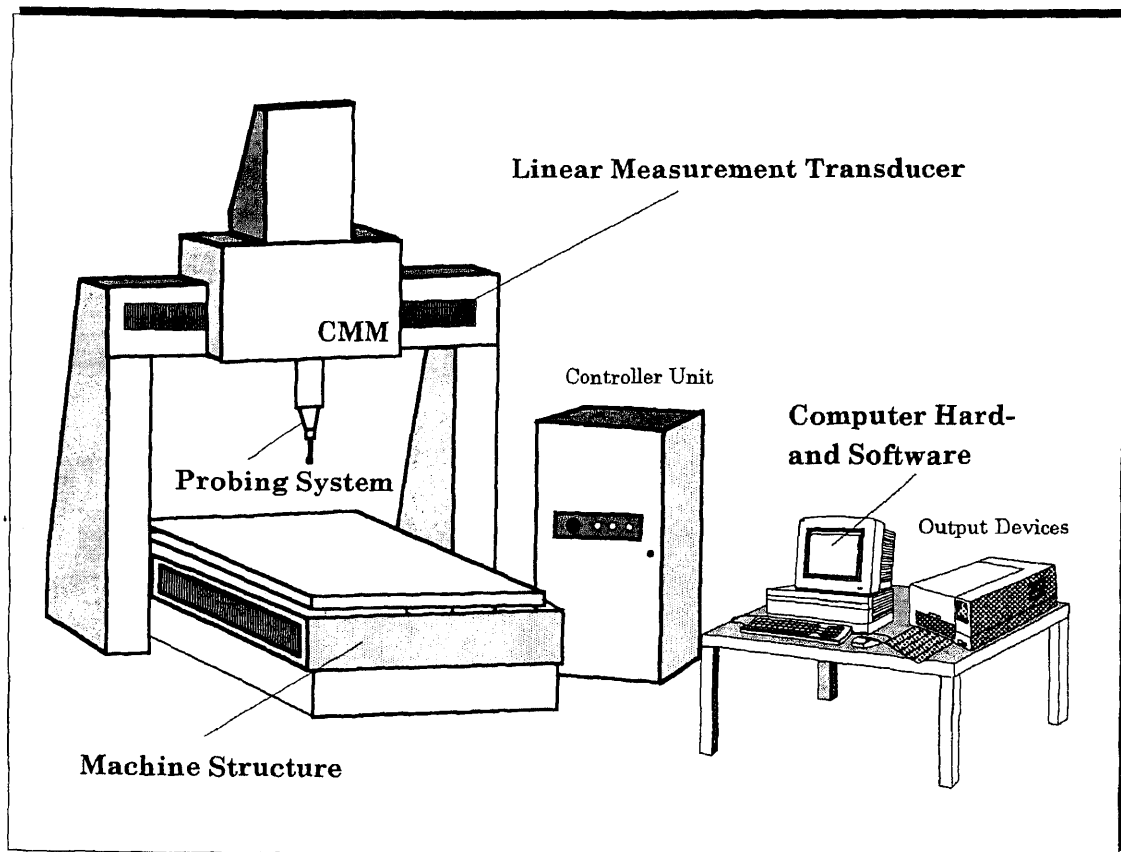


Figure 3.2 Coordinate Measuring Machine Components

3.2.1 Machine Structure

The machine structure is the physical base with three perpendicular axes of travel. This structure has to fulfill the following requirements:

- *Rigid construction to minimize unintended movement between machine components.*
- *Thermal stability to minimize machine deformation through thermal expansion.*
- *Insensitivity to mechanical vibrations.*
- *Good damping characteristic.*
- *Long-time stability.*

Traditionally cast iron and granite, are used for the machine structure. Granite, like Diabas or Gabbro, is mined in Sweden and South Africa and is suitable because of its mass (density: 3 kg/dm^3 [18]), vibration damping characteristic, long-time stability, corrosion-resistance and thermal stability (heat expansion coefficient: $\alpha \approx 8 \cdot 10^{-6}/\text{K}$ [18]). The thermal conductivity of granite ($\lambda \approx 3.5 \text{ W/mK}$ [3]) is very low, which can lead to temperature differences and irregular deformation of the guide ways. Machines with a granite structure are preferably used in a controlled environment.

Today aluminum and more exotic materials like ceramic, invar or carbon-fiber are employed as machine structure materials. Aluminum is a somewhat surprising choice because of its high heat expansion coefficient of $\alpha \approx 24 \cdot 10^{-6}/\text{K}$ [3] as compared to cast iron ($\alpha \approx 10 \cdot 10^{-6}/\text{K}$ [3]) or granite. Aluminum's advantage lies in its high thermal conductivity of $\lambda \approx 220 \text{ W/mK}$ [9] as compared to cast iron with $\lambda \approx 25 \text{ W/mK}$ [9] or granite.

The CMM manufacturers can achieve the thermal stability in one of two ways, either by choosing a material which reacts very slowly to temperature changes, like granite or ceramics, or by choosing a material like aluminum which reacts very quickly to changes. In both cases the employed material for the single structure components should be the same to reduce the effects of expansion and contraction due to temperature changes. Today's modern machine beds are designed as frameworks by using a finite element analysis to assure an optimum combination of high stiffness and low weight.

The bearings employed on CMMs have a direct impact on the accuracy of the machine because of their effect on every motion along its axes, and hence high demands are made on the bearing construction. The most important requirements can be listed as:

- *No or very little friction.*
- *Highest linearity.*
- *No short-periodical positioning deviations.*

The following types of bearings are mostly used on CMMs:

- *Air Bearings*
- *Roller Bearings*
- *Recirculating Bearing Packs*

Air Bearings are the most frequently used type of bearings on CMMs. They are the best choice in regards to accuracy, because they move without friction and are, therefore, wear-resistant. Air-bearings are self cleaning and insensitive to dirt, but for shop-floor applications, where the air is filled with oil, the dirt deposit can stick to the guide ways and then cannot be removed

by the streaming air. For these applications, the guide ways have to be protected or they need to be cleaned daily or weekly depending on the environmental conditions. In addition, air bearings are insensitive to mechanical influences, whereby small air-gap deviations under load guarantees high stiffness. The small air-gap of approximately 6 μm barely consumes any air, which is quite important for economic reasons.

Roller Bearings are a good choice but they provide a somewhat lower level of accuracy than air bearings. Roller bearings are sturdier and can function in an atmosphere containing some dirt and dust.

Recirculating Bearing Packs combine the high accuracy of air-bearings and the insensitivity to use in the harsh factory environment by utilizing completely sealed bearing packs. They have a small friction coefficient and show only a small slip-stick effect, which guarantees high repeatability and accuracy of positioning. Also, significantly higher accelerations make shorter measuring cycles possible, which is another plus for shop floor applications.

CMMs utilize direct-current (DC) motors to drive the axes. These motors power a friction wheel with a friction rod, a gear with a gear rack or a V-belt pulley with a ribbed V-belt to transform the revolving motion of the motor into linear motion along the axes. The power transmissions enable high acceleration and deceleration in a short period of time (important in case of collision) and they guarantee high positioning accuracy based on their small play. By attaching the driving elements at the center and close to the pivot of the moving part the leverage by the moment of inertia is extremely small, which further influences the machine's dynamics favorably.

3.2.2 Linear Measurement Transducers

At the three perpendicular traveling axes of a CMM, linear measurement transducers are mounted which physically describe the reference coordinate system or what is known as the machine coordinate system. The function of the measurement transducers is to provide a position feedback within the working range. They consist of a scale and an encoder system, with one of them mounted to the moving part on each travel axis. CMMs commonly employ incremental linear measuring systems, where the dimensional embodiments are realized with:

- *Gear racks*
- *Precision screw spindles*
- *Scales*
- *Inductive rulers*
- *Laser interferometers*

Out of all the mentioned systems, the most commonly used linear measuring systems are *Scales* with photoelectric readers. The scales are either made from stainless steel or glass, on which a graduation with approximately 8 μm [70] wide marks and gaps of the same width, is applied. In the past, stainless steel scales were frequently used because stainless steel has nearly the same thermal expansion coefficient as the steel parts usually being measured. Therefore, dimensional correction due to different thermal expansions between the scales and the part was not necessary to be considered. Today the scales are generally made from a glass-ceramic named as Zerodur. Zerodur is a transparent material and has a thermal expansion

of almost zero ($\alpha = 0.05 \cdot 10^{-6}/K$) [13]. Different thermal expansion values between the glass-scales and the object being measured are corrected easily by today's powerful computer software. Stainless steel scales and glass scales are used with reflected light whereas the transparent glass scales can be used with transmitted light in addition to reflected light (Figure 3.3).

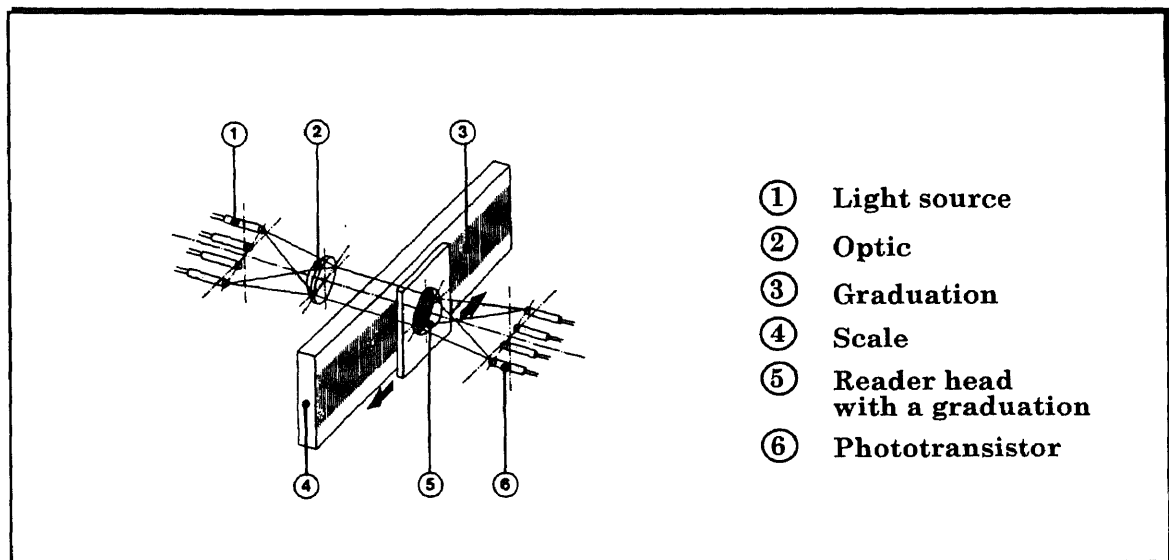


Figure 3.3 Linear Measurement Transducer Zeiss Phocosin [70]

In both methods a photoelectric reader with a graduation of the same style as the scale, slides over the scale without any contact. Depending on the location of the reader on the scale, light emitted by diodes is either blocked or received by the phototransistors. When the reader head moves over the scale, the phototransistor's output is a sinusoidal waveform, whose cycle corresponds to a single step on the graduation [39]. From the received sinusoidal wave, a displacement is registered, but no information can be obtained about the displacement direction. Therefore a second staggered photoelectric encoder is applied which outputs a phase shifted sinusoidal waveform that is compared to the first one to give the necessary information

about the displacement direction. The phototransistors are usually connected in pairs, in order to cancel out the constant voltage added to the modulation. Resolutions of as low as $0.025\ \mu\text{m}$ are obtained by an electronic circuit which interpolates the analog signals. Due to the fact that the encoder head slides with no contact over the scale, friction, backlash and wear are not generated, which makes this linear measuring system maintenance-free. Care has to be taken when being used in a dirty environment like a factory floor. The scales and encoders should be protected thoroughly to ensure that no dirt can deposit on the scales so that the proper function is not affected and friction between the reader head and the scale is not generated.

Laser interferometers are used only for some special designs of CMMs, but in the future it can be expected that they are more frequently utilized for large gantry-type CMMs, where they can guarantee a high level of accuracy.

3.2.3 Probe Systems

The probe system is the principle item of a CMM. Its function is to identify a coordinate point on the object surface. The variety of probe systems used on CMMs is numerous (Figure 3.4). In the beginning, when CMMs were introduced, hard probes were applied. Today, electro-mechanical, electronic and optical probe systems are exclusively used. The type of probe system installed on a CMM determines its capability and application based on system specific characteristics. The two basic types of probe systems are:

- *Contact Systems*
- *Non-contact Systems*

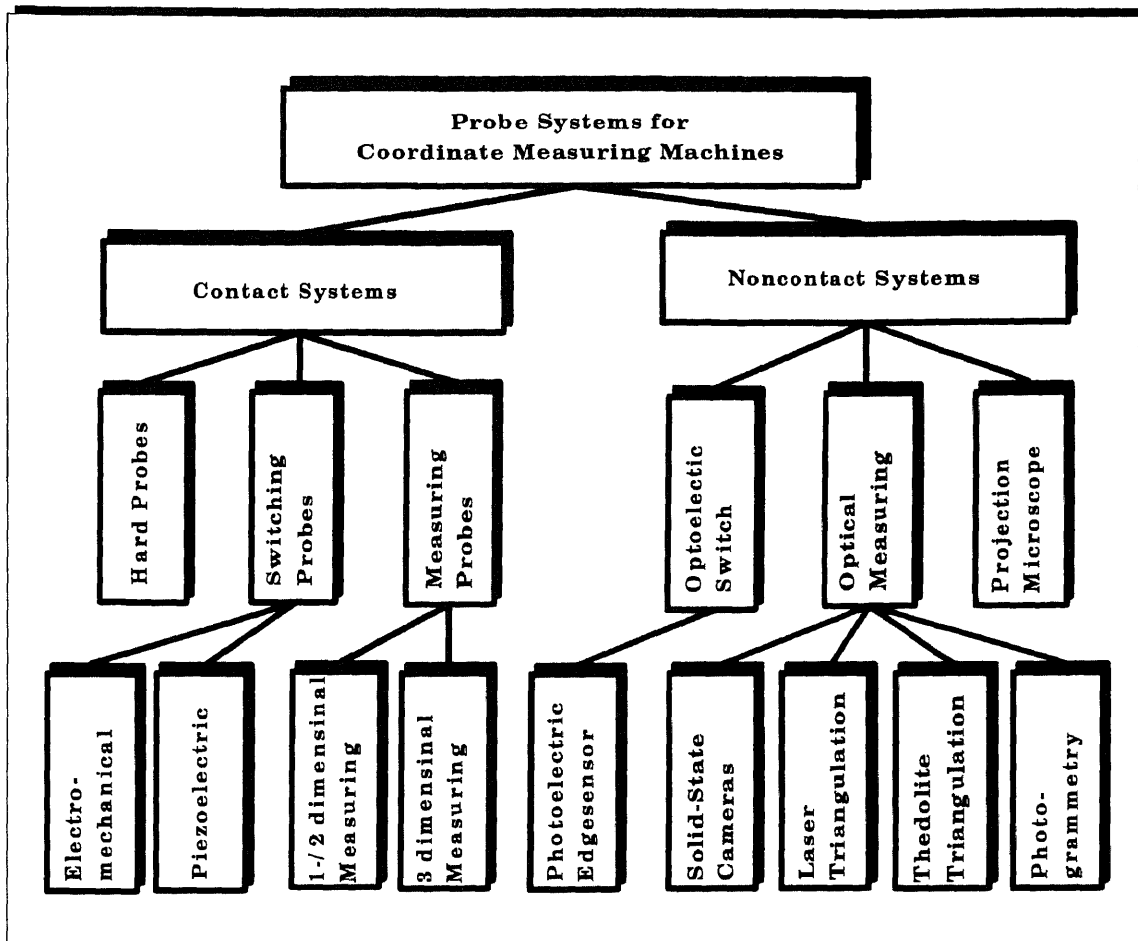


Figure 3.4 Probe Systems for Coordinate Measuring Machines [41]

Contact Systems carry a stylus tip at the end of the probe system, that makes physical contact with the object surface. Usually, the tip is in the shape of a sphere and made out of a ruby. Ruby, a precious stone, is a very homogenous, hard and wear-resistant material. High-precise spheres can be produced, with deviation of just $0.25 \mu\text{m}$ [70] in the shape of an ideal sphere. When contact is made with the object surface the electronic probe system triggers an electric signal to record the current position instantaneously by reading the scales of the CMM. Contact systems are the most frequently used

sensors. For some industrial applications, as in the measurement of very flat, fligree or soft objects, they are limited in use and sometimes not applicable.

Non-contact Systems are optical devices where no stylus is used to detect the part surface. These systems are mostly used for two-dimensional measuring of flat parts, like electronic boards or objects made of soft material, where a contact system might deflect the part being measured. Another advantage of non-contact systems is their measurement speed. Depending on the measuring task, they can be as much as three hundred percent (300 %) faster than contact systems. In addition, problems like stylus compensation, friction angles or changing contact forces are not encountered by these systems.

3.2.3.1 Contact Probe Systems

Switching Probes

With the previously mentioned hard probes, only manual measurements were possible. In addition, contacts (called hits) had to be done very carefully, since too large contact forces can lead to elastic or even permanent deformation of the stylus. In the process of developing CNC-Coordinate Measuring Machines, a probe had to be developed which could deflect in each space direction, could generate an electric trigger signal and could come back to its definite zero-position after contact.

The first system developed that had these characteristics was an Electro-Mechanical Probe System, like the one shown in Figure 3.5. The system contains a spring pre-stressed kink point, that is realized by a three-point-base made up of spheres and cylinders. The contact points are designed

as electro-mechanical switches in series. When the probe is deflected by a probing force, one of the contacts opens and generates an electric impulse. A switching delay occurs which is dependent on the length of the stylus and the deflection direction. After deflection, the spring force pushes the contact plate back to its original position and closes the contact again.

The second switching system developed makes use of a piezo crystal to generate an electronic signal. This *Piezoelectric Probe System* is equally sensitive in each direction and reacts either to pressure or to acoustic waves. The piezoelectric sensor is placed in front of the mechanical kink point described in the previous system. It gives an electronic impulse at contact forces as low as 0.01 N, even before the mechanical contact is displaced. By separating the signaling device (piezo crystal) from the deflection mechanism, a higher pre-stress on the mechanical system can be applied, as compared to the Electro-Mechanical Probe System. This fact enables the use of longer and heavier stylus configurations. The sensitivity of this probe system is so high that even acceleration forces, vibrations, or reseating of the mechanical system can cause a trigger signal. Therefore, a post logic sensor has to confirm that each signal was correctly generated by a hit, and then allow the recording of the current coordinates.

Switching probes are dynamic probe systems, i.e. an electric signal is only produced when the probe is moving and the stylus is making contact with the measuring object. Therefore, these systems are limited in application to small holes, where the stylus cannot accelerate to a reasonable speed before a reading is taken. Switching probes are mostly used when an object has to be measured very fast by single hits. In an automatic run, sixty hits per minute can be achieved by such a system.

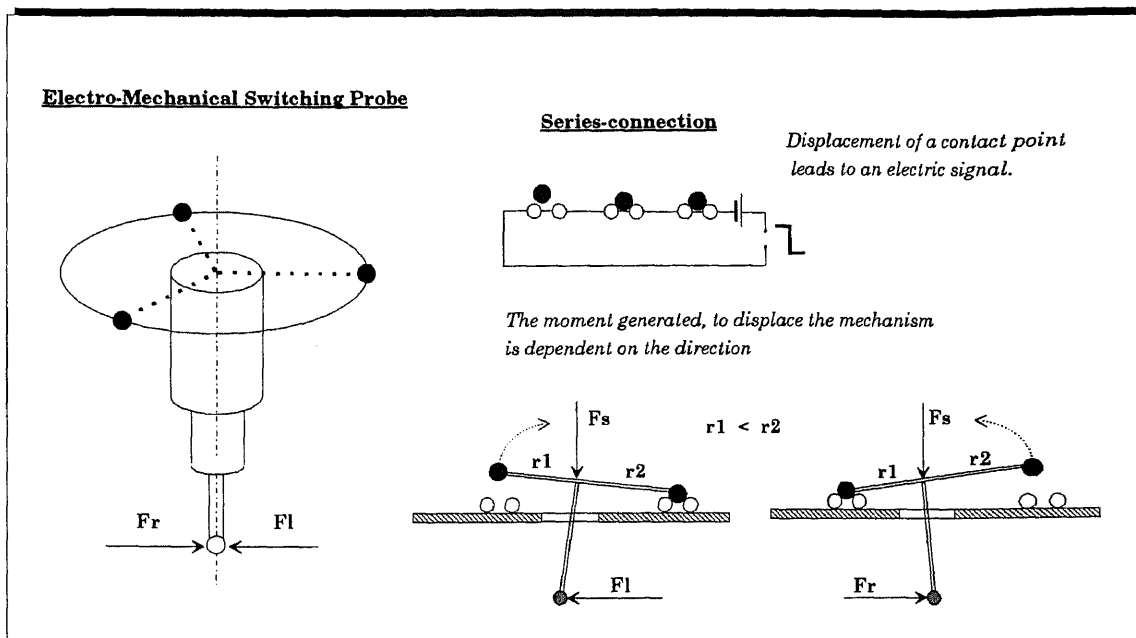


Figure 3.5 Principle of an Electro-Mechanical Switching Probe [41]

Measuring Probes

With the introduction of the first three-dimensional measuring probe in 1973, the contact metrology arrived at a new quality level. The measuring accuracy increased tremendously on all kinds of Coordinate Measuring Machines. The production of large bridge type CMMs now became possible, because with a measuring probe the measurements can be done without any motion, and therefore probing forces cannot lead to deformation of the machine structure. A measuring probe can be built out of flexible parallelograms, as shown in Figure 3.6. For a three-dimensional probe system three flexible parallelograms are present, one for each axis direction and therefore the stylus is able to deflect in any direction in space. The displacement of a flexible parallelogram is measured either by an induction measuring system or by a photoelectric sensor with a graduated scale, like the one used for the linear measuring transducers on the CMM itself. An

electro-mechanical stop mechanism built inside each flexible parallelogram can clamp the parallelogram in its center position. This prevents a deflection of one or two axes directions. The three-dimensional measuring system can hereby be reduced to a two- or even one-dimensional probe system, which might be necessary for some measuring tasks. When the stylus touches the object surface, a contact force ($F_c > 0$) normal to the surface at the contact point is produced, which displaces the probe head's parallelograms. The deflection of the single parallelograms is proportional to the probing force components, according to Hooke's law $F \sim \Delta s$. A deflection is recognized by the machine motion controller which stops the drives instantaneously. After the machine has stopped the measuring probe takes control over the retract motion till the parallelograms are back at their zero positions ($F_c = 0$). When the CMM's own oscillation diminishes down after approximately 0.4 seconds, an electric signal is produced which leads to the recording of the coordinate position. Measurements of this kind where the parallelograms are brought to standstill at their zero positions are called static measurements. The probe is called a Nulling Probe.

Measuring probe systems have the capability to measure in a position other than the zero point measurement position. The measurement can be done when the probe is displaced because the amount of deflection (Δs) is measured by the probe's measuring systems. To determine the probing point, the amount of probe deflections are either added or subtracted to the scale readings of each axis direction (Figure 3.7). When the motion controllers detect a contact and the probe head retracts, continuous readings of the probe deflections and the CMM scales are done to calculate a three-dimensional characteristic (Figure 3.8).

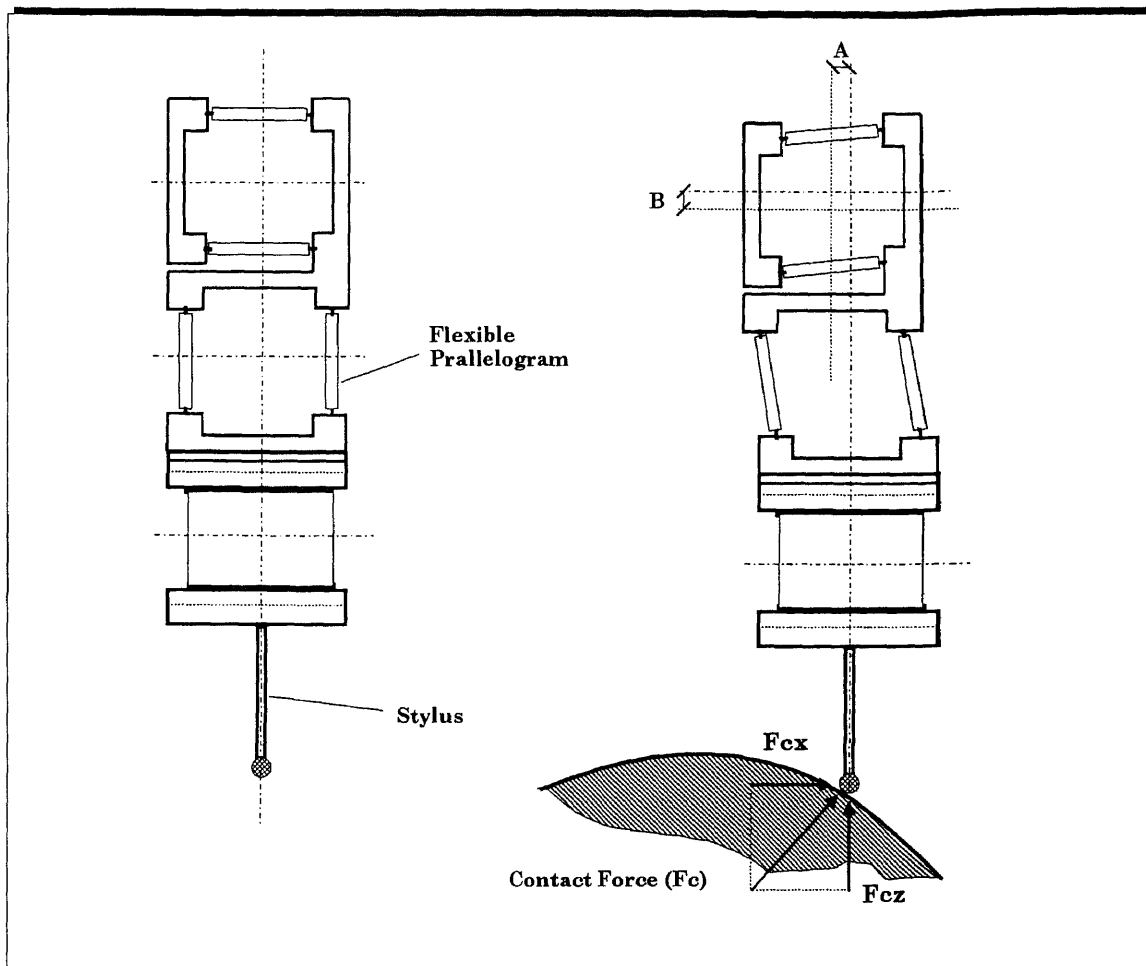


Figure 3.6 Principle of a Measuring Probe with Flexible Parallelograms

The final registered probing point is determined at an optional contact force between zero Newton and 0.5 Newton ($0 \text{ N} \leq F_c \leq 0.5 \text{ N}$). This kind of measurement with a measuring probe system is also called *Dynamic Single Point Probing*. An advantage of this method is that measurement uncertainties during the retract motion are balanced to minimize the influence of chance.

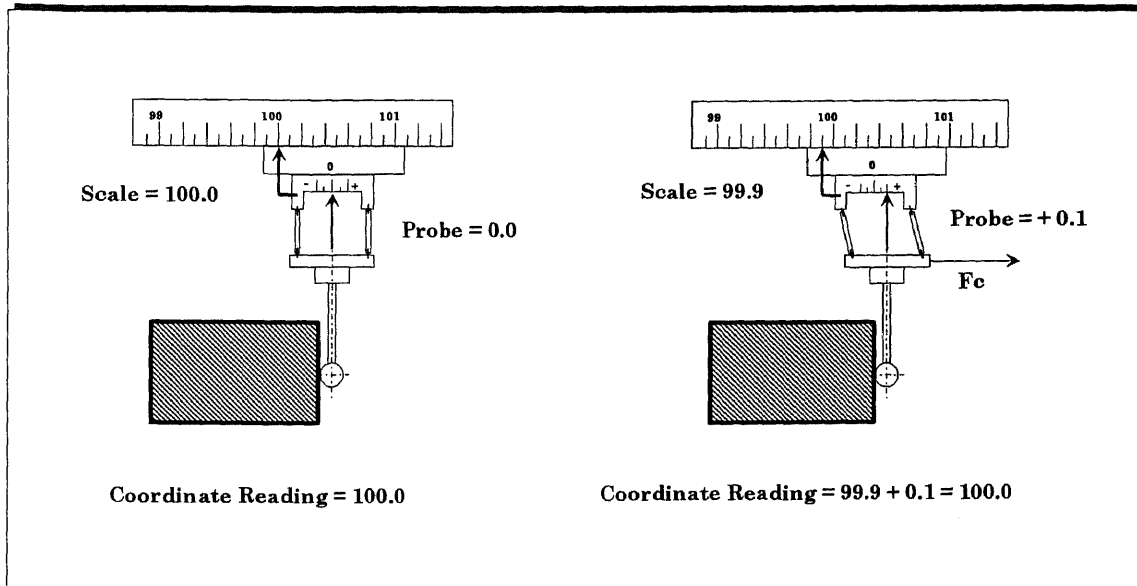


Figure 3.7 Null Probing versus Deflected Probing [70]

Another way of probing using measuring probes, beside the single hit method, is called *Scanning*. Scanning is the probing method where the measuring probe continuously measures an object surface with a known constant contact force, and transmits measured data either periodically or after a lengthy continuous sequence. Using this method surfaces oriented in any direction in space can be measured. The stylus radius-correction can be done for each single measuring point since the normal direction to every measured point is recorded as well. Measurements in the scanning mode are less accurate than in the single point probe mode because of friction between the part surface and the stylus. By using incorrect scanning speed, probing force and surface curve radius parameter proportions, a slip-stick effect can occur which leads to incorrect measurement of the deflections and to vibrations in the probe system. The repeatability of these scanning factors is not guaranteed from part to part, and their dynamic interaction generates some dispersion of the measured points. Nevertheless, scanning obtains

faster measurements with a higher point density especially for scanning of contoured part surfaces.

Reverse engineering by scanning small scale models can provide unknown engineering opportunities, by uploading the measured coordinates to a CAD-system. Single purpose measurement devices like the one used for measuring gears can be replaced by a CMM with a scanning capability.

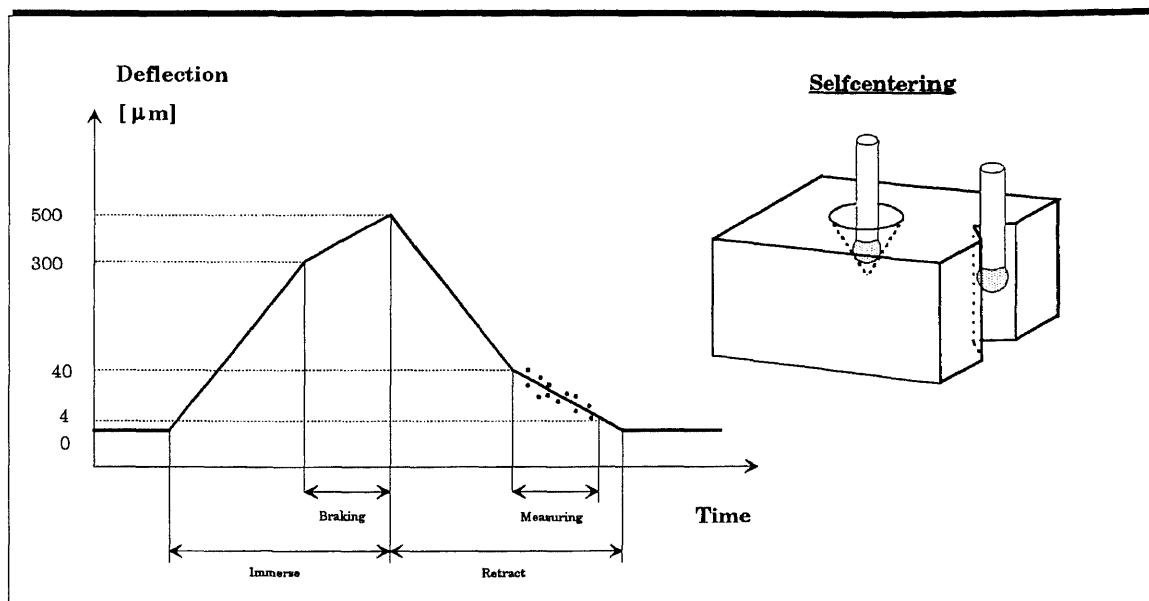


Figure 3.8 Dynamic Single-Point Probe Method and Selfcentering Probe Method

Another useful measuring feature available through a measuring probe system is the *Self Centered Probing* in one or two directions. The deflection of the probe system in one or two directions is readjusted as long as a motion in a pre-given direction is possible. Self Centered Probing enables for example the determination of the center of a taper hole, the middle position of a V-form groove, or the middle point between two tooth flanks of a gear.

3.2.3.2 Non-contact Probe Systems

Laser Triangulation

A popular laser based device used on CMMs, is the single-spot laser triangulation method illustrated in Figure 3.9. This method uses a low-powered laser beam for distance measurement. The laser beam directed perpendicular to the part surface, reflects on the surface and is received by a light sensitive detector, like a CCD-array (Charged Coupled Device), at an angle of approximately 25 degrees. A change of standoff distance from the sensor to the part surface results in a lateral shift of the detected light spot on the array, which is directly related to the standoff distance. Laser Triangulation Probes on CMMs are mostly used for scanning surfaces, where the generated signal is used for readjusting the probe's path over the part surface. When Laser Triangulation Probes are used for point-to-point measurement, they provide, through their standoff distance, enough clearance to the part so that no collision of the probe with the part will occur. The use of a Laser Triangulation Probe is limited for deep holes and situations where the reflected light beam is blocked from reaching the detector eye.

Solid-State Cameras

Machine vision is being used more frequently in every facet in industry including in CMMs. To be classified as machine vision, a system has to have the following four primary functions: image formation, image preprocessing, image analysis, and image interpretation [68].

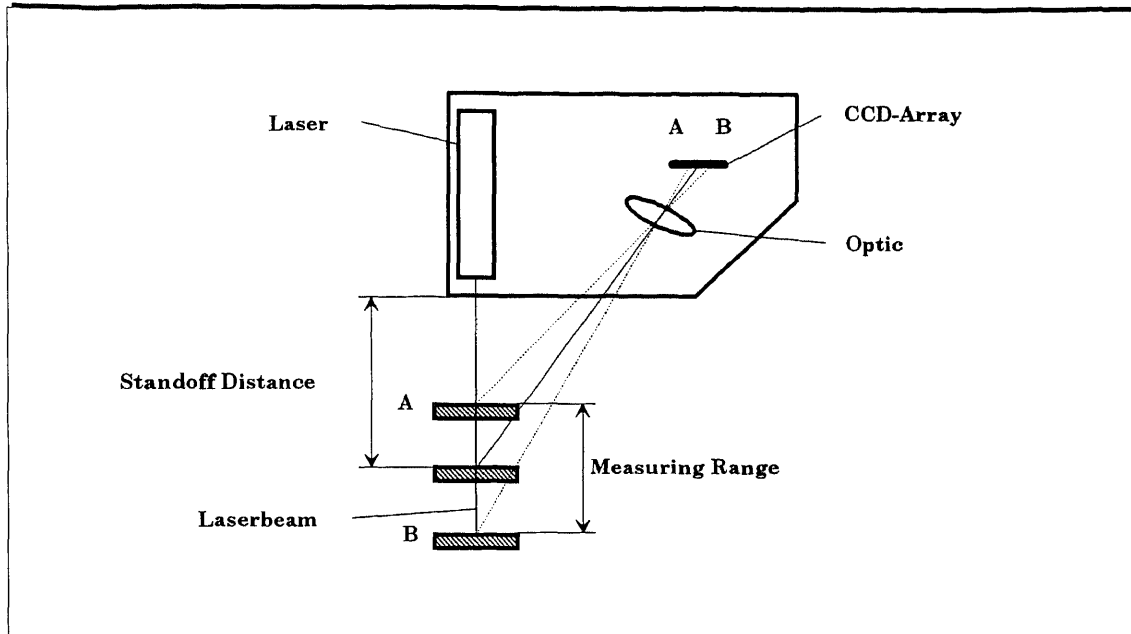


Figure 3.9 Laser Triangulation Probe [41]

The function 'image formation' is compiled by a camera probe, as the image sensing device. Two types of cameras are used for machine vision systems, vidicon cameras, which are the kind of cameras used for consumer video products, and solid-state cameras which are almost exclusively used for CMM applications, and described as follows.

A solid-state camera consists of an imaging optic and a large number photosensitive elements whose signals are accessed and stored in a computer. For the photosensitive image sensor a charged-coupled device (CCD) is usually employed in this kind of camera. It contains matrix arrays of small, accurately spaced photosensitive elements. When light, passing through the camera optic, strikes the array each photosensitive element converts the portion of light falling on it into an analog electrical signal. The entire image is thus broken into an array of individual picture elements, called pixels. In the image preprocessor the analog voltage values of each pixel are converted

into corresponding digital values which can be processed by a computer. Depending on the number of possible digital values that can be assigned to each pixel, a vision system is either classified as binary or gray-scale. The binary system assigns only the values 0 or 1 depended on a predetermined threshold level, whereas the gray-scale system can assign 2^n values, with n as the number of bits available (for a 8 bit system is this 254).

Theodolite Triangulation

Theodolites, which are usually used in geodesy, can be used in pairs as a Coordinate Measuring Machine. The Theodolites are laser based devices which are working on the same triangulation principle as described for the Laser Triangulation Probe. Instead of being mounted in a rectangular coordinate system they are mounted on portable tripods (Figure 3.10). The connection line between the two Theodolites is used as the reference line for the coordinate system. The measuring points have to be marked at the object, so that the user can manually direct the two laser beams on them. Before use the system is calibrated with a measuring rod at the measuring site. This portable kind of CMM is usually used for measuring extremely large objects, like airplanes, ship or automobile bodies, which cannot be transported easily to a stationary CMM.

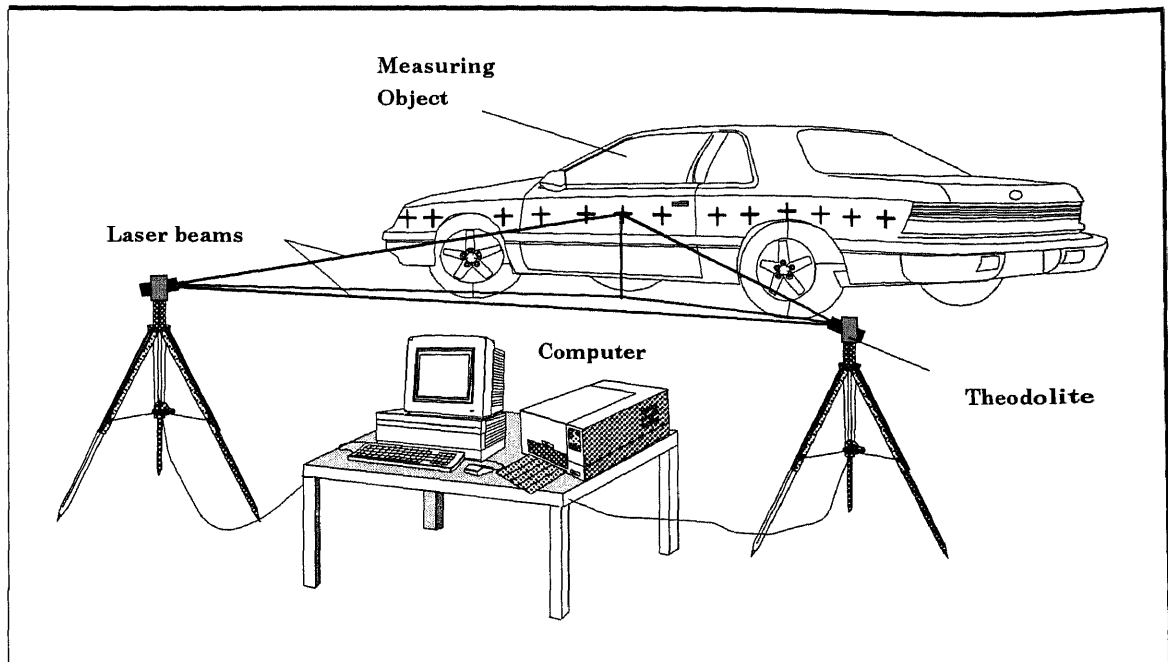


Figure 3.10 Theodolite Triangulation

3.2.4 Computer Hardware and Software

The computer hardware and the applied CMM-software determine the capabilities and the versatility of CMMs. From today's standpoint of CMM evolution, five automation levels can be distinguished [41]. Figure 3.11 illustrates this in the form of a matrix, in which the automation criterias are shown against the five levels of automation.

Today's CMM market shows that there are three major categories of automation that the machines can be grouped into. This three categories can be described as follows [41]:

- *Manual guided CMM with position display of all axes.*
- *Manual guided CMM with computerized data processing and reporting.*
- *Direct-Computer-Controlled (DCC) CMM with computerized data processing and reporting.*

Criteria	Axes Motion	Machine Control	Probing	Stylus Change	Display	Data processing	Program- ming
0	manual	N/A	manual	manual	digital	manual	N/A
1	manual	N/A	manual	manual	digital	Computer	manual
2	Motor	manual	automatic	manual	digital	Computer	manual
3	Motor	CNC	automatic	automatic	digital	Computer	manual
4	Motor	CNC	automatic	automatic	digital	Computer	Teach-in
5	Motor	CNC	automatic	automatic	digital	Computer	Off-line

Figure 3.11 Levels of Automation of Coordinate Measuring Machines

The trend in CMM evolution is more and more going in the direction of DCC-CMM with full capability for integration into the vision of Computer Integrated Manufacturing (CIM), where the computer forms the heart of a CMM system. Nevertheless, there is and always will be a market for low cost, manual guided machines which can be applied on the shop-floor next to the production machines for quick quality checks and which can be operated by the shop-floor personnel.

The computer hardware being used is versatile, and varies from Personal Computers (PC) to networked workstations. The computer hardware needed can be usually purchased from the CMM manufacturer directly, or if a suitable hardware environment for the CMM software already exists at the customer site, the CMM software can be loaded onto the customer's system. Input devices are generally in the form of a keyboard and

a control box that are supplied with the machine. Today tablets, digitizers, light-pens and touch-screens for shop-floor applications or any combination of them are also being used. The output devices are as versatile as the input devices and vary from CRTs, disk drives or tapes to peripherals like printers or plotters to document the results.

The computer in a DCC-CMM has to accomplish diverse tasks and the CMM software enables the system to fulfill its potential. The five major tasks the computer has to accomplish are:

- *Control the Machine Motion*
(Point-to-Point, Straight-line, Scanning, etc.)
- *Align the Part*
(Reference coordinate system, Part coordinate system)
- *Make Corrections*
(Radius compensation, Stylus deformation, Temperature, etc.)
- *Calculate*
(Substitute Elements, Intersects, Functions, Transformations, etc.)
- *Evaluate*
(Nominal-actual evaluations, Test reporting, Statistic, etc.)

The CMM problem oriented software, which usually runs on a UNIX based or a VMS operating system, was tremendously developed in the last few years. In the early stage of DCC-CMMs it was necessary to program the measuring routines in a standard program language like FORTRAN. Today most of the CMM manufacturers offer their own problem oriented programming language to program their machines in. The programming systems on today's CMM market are user friendly and menu driven, which apply a plain English style command set that is easy to remember and is also

self explanatory. In addition to the basic CMM software the customers usually can choose according to their needs from a wide variety of special software modules to solve complex measuring tasks. These special softwares also offer advanced evaluation and documentation capabilities.

The disadvantage of the manufacturer specific systems is that they are mostly incompatible with other CMM manufacturer's systems. This means that programs developed on a specific CMM cannot be directly used on a CMM from a different manufacturer. It also means that after a buying decision has been made, the customer has to stick to the CMM manufacturer's offered products in the future. Therefore today's CMM customers wish to have a machine and computer system that employs an independent programming system with a neutral problem oriented programming language. Source programs developed in a neutral format can be adjusted for a specific CMM by a post processor, and then downloaded into the machine.

N.C.M.E.S. (Numerical Controlled Measuring and Evaluation System) is such a neutral problem oriented programming language [41]. It was developed in accordance with EXAPT (Extended Subset of Automatically Programmed Tools), an NC-language for programming machine tools.

Another aspect of developing neutral formats is to integrate dimensional inspection by sharing data with a CAD-system to decrease CMM programming time. Also, reverse engineering can be used in the development by measuring unknown part shapes whose surface data can then be processed by a CAD-system. As an improvement on N.C.M.E.S., Computer Aided Manufacturing International (CAM-I) developed a neutral format called DMIS (Dimensional Measuring Interface Specification) which

makes a bi-directional data exchange between a CMM and a CAD-system possible (Figure 3.12).

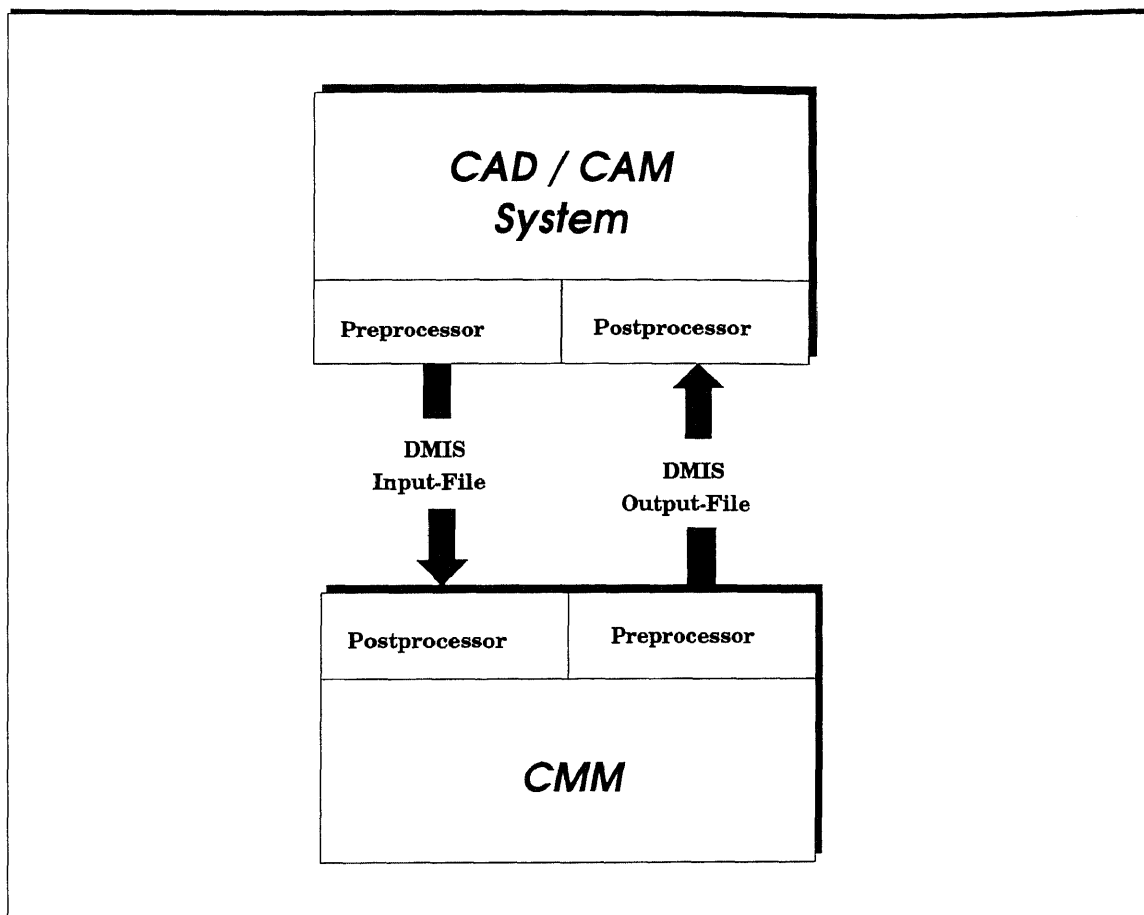


Figure 3.12 Bi-directional Exchange of Data with the DMIS Format

CHAPTER 4

ACCURACY OF COORDINATE MEASURING MACHINES

4.1 Introduction

The accuracy of a Coordinate Measuring Machine is very difficult to define due to its complexity, i.e. as a consequence of its spatial coordinate system and the large number of subassemblies [57]. The numerous existing types of CMMs with their different levels of automation makes this task even more difficult.

The measured coordinates are combined into geometric elements in such a way that the measuring tasks can be solved. Owing to deficiencies of the CMM in its operation and its environment, the obtained coordinate values are subject to measuring deviations and therefore the resulting geometric elements are also subject to deviations. The measurement deviation when using a probe to measure any point in the work envelope, can be represented by a three-dimensional vector (Figure 4.1). This vector generally cannot be determined at all points in space with adequate accuracy using the currently available measurement methods [57]. Therefore it is not possible to derive a task specific measurement uncertainty for the various positions in the work envelope of the CMM. To define the accuracy of CMMs, either individual components of the measuring deviations or the occurring measuring deviations for selected measuring tasks are being used.

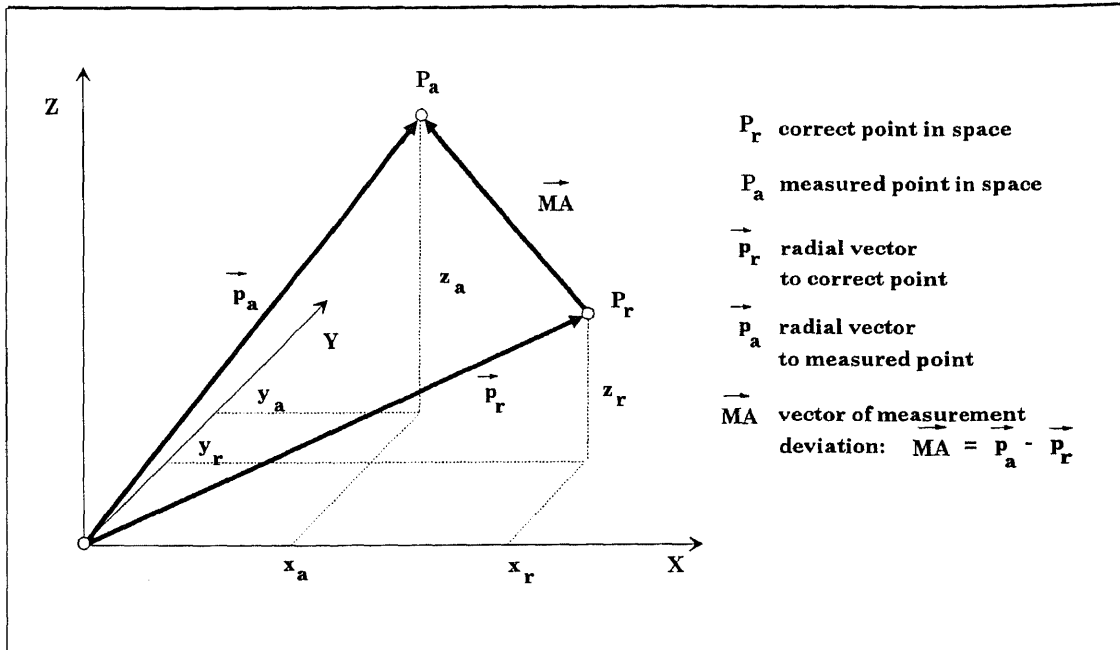


Figure 4.1 Vector of Measuring Deviation [57]

Finally, it must be pointed out that characteristic accuracy parameters of machine tools and Coordinate Measuring Machines differ fundamentally. The machining tool is moved to a specific position which is specified by the entered set data. The deviation between the entered required position and the actual position assumed is of great importance for calculating the accuracy of the machine tool. On a CMM the coordinate values of the probing point are determined by linear measuring systems in relation to a reference system. Initially, the precision with which an entered position is approached is of secondary importance for the accuracy of a CMM. The important aspect is how accurately the output coordinate values specify the position at which the probe system actually arrives.

4.2 Measuring Deviation

Like every other measuring device that is used in metrology, a CMM has a certain degree of measuring accuracy, or in other words the measured part dimensions deviate by a certain value from the real value of the dimension. The measuring deviation is a very important criteria for comparison of the different kinds of measuring devices, and the knowledge of its value is essential. The value of the measuring deviation is different for the measuring device manufacturer from that of the user of the device. The manufacturers test the measuring devices to guarantee the measuring uncertainty stated by them, whereas the user is concerned about the range within which the real value of the dimension can be expected. The tighter the tolerances of the parts to be measured, the more important the measuring uncertainty of the chosen measuring device is. When the user wants to avoid the possibility of allowing parts or subassemblies that are out of tolerances to be accepted, or to take out of the process the parts that are "in tolerance", he has to make sure that the manufacturing tolerances for producing parts is limited by the amount of the measuring deviation (Figure 4.2). The measuring uncertainty "decreases" the tolerance range and therefore it is important to have measuring devices with a minimum of uncertainty. In today's manufacturing world, the trend of keeping the tolerance at a minimum is of tremendous value and so the measuring device industry responds with new or improved measuring devices to keep up with this trend. This correlation has been known in metrology for some time and is called "The Golden Rule of Metrology". It states that the measuring uncertainty should be ten times smaller than the manufacturing tolerance.

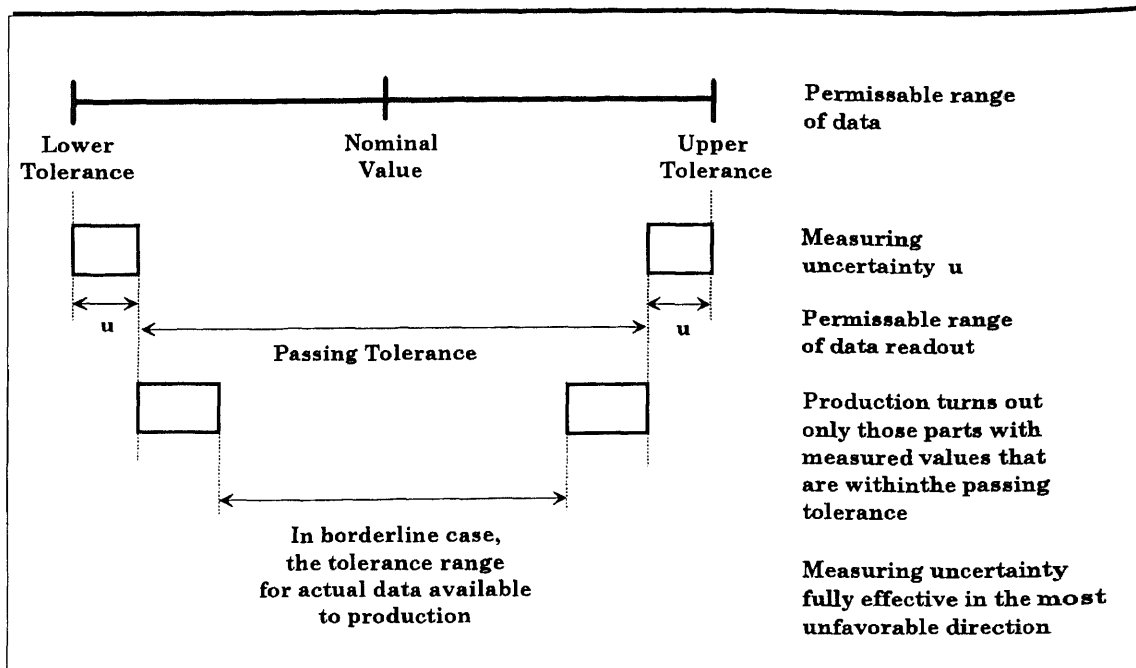


Figure 4.2 Effect of the Measuring Uncertainty on the usable Tolerance in Production [32]

The measuring uncertainty consists of two different types of deviations, one which is caused by systematic errors and the other by random errors during measurement. A clear distinction between the causes for systematic and random deviations is almost impossible. Systematic deviations if identified, can be corrected. They can be caused for example by the inspector, by defective measuring devices, by improper calibration or by an insufficient measuring environment. For identification of systematic deviations a comparative measurement can be carried out in which all limiting quantities, except the one which is under investigation, are kept constant. Because of the fact that the comparative measurement contains systematic and random deviations itself, it is often very difficult or even impossible to determine a corrective value for the systematic deviation. That does not mean that comparative measurements should not be done. Random deviations are caused by imperfections of all kinds during measurement. Its

value and the value of the real dimension can be investigated by carrying out repetitive measurements in which all limiting quantities are kept constant for all the measurements. The spread around an average value in a histogram of the measured values shows the random deviation, which in statistics is also known as the standard deviation. Because of time and economic limits, measurements can be repeated only a certain number of times and therefore the real value of a dimension cannot be stated with 100 percent confidence. Therefore, the measuring result is declared with a predetermined confidence interval within which the real value can be expected for a certain percentage of time.

4.3 Factors Affecting CMM Performance

The CMM, a highly sophisticated and precise measuring device, is effected in its performance by various factors which can be classified into three major categories. The errors which lead to a lower level of performance are mostly of systematic rather than of random nature. To obtain a high level of performance it is absolutely essential that the user select the appropriate machine for his specific applications. Beyond this, the CMM has to be located in a suitable environment and has to be operated by well trained and educated machine operators. The three major categories of factors affecting the performance are:

1. *Environment*
2. *Machine*
3. *Operation*

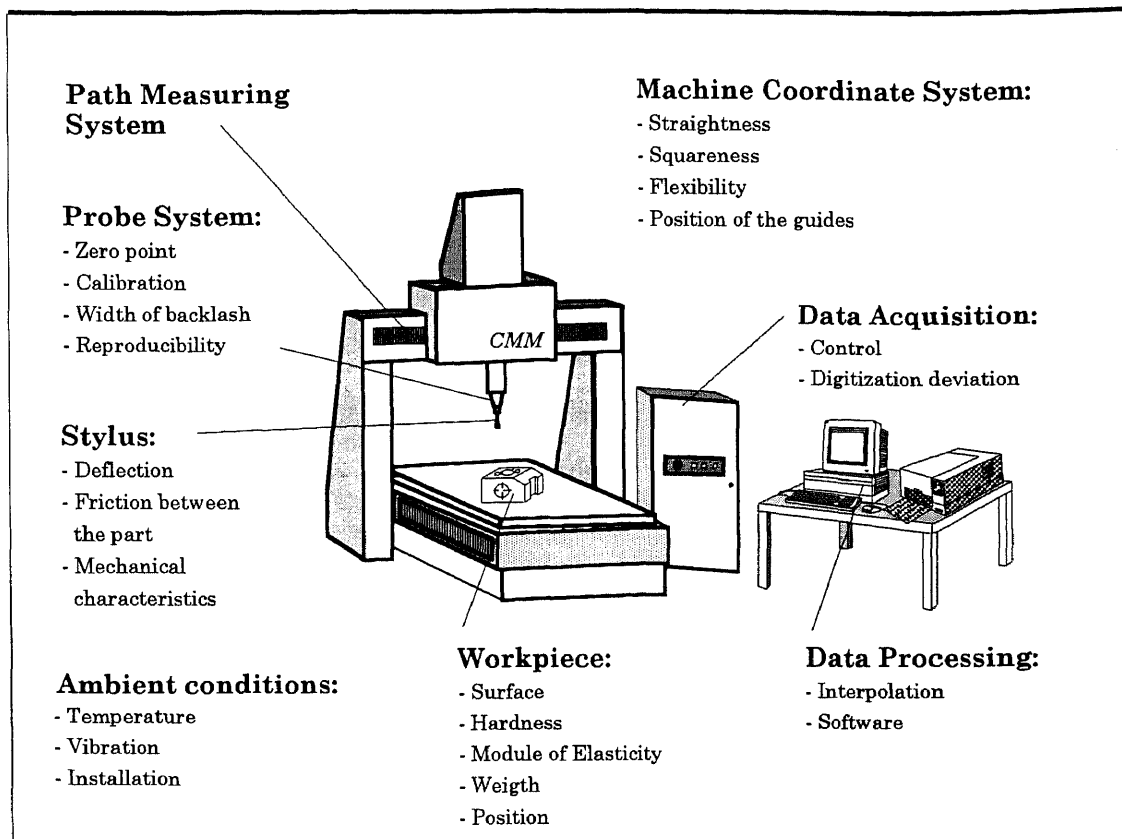


Figure 4.3 Factors Influencing CMM Performance

4.3.1 Environmental Factors

Environmental factors are very critical for the correct performance of a CMM and it is the responsibility of the user to provide an acceptable environment at the installation site [5]. The CMM manufacturers provide their customers with environmental guidelines under which the manufacturers guarantee the specified performance of the machine. An environmental guideline from the CMM-manufacturer Leitz Messtechnik GmbH, Germany for their machine Leitz PMM 181210 is listed in the Appendix A. These can vary somewhat from manufacturer to manufacturer. If the user cannot or does not want to provide the specified environmental conditions, then he has to accept

a reduced performance for his machine. The most critical environmental factors affecting CMM performance are:

- *Temperature*
- *Vibration*
- *Airborne Particles*

Temperature is the most critical of all the environmental factors, and its effect is often misjudged. The entire machine structure, especially the orientation and shape of the guide elements and scales, deforms as a function of the ambient temperature. This deformation, caused by temperature fluctuations and spatial temperature gradients over time, is very difficult to predict or to simulate quantitatively. This further leads to a loss in measuring accuracy of the CMM. Therefore the ambient temperature must lie within a specified temperature range and maximum temperature must not be exceeded. Spatial temperature gradients of the surrounding medium, draft and thermal radiation which are caused by surrounding machines, walls, windows, light fixtures or sunlight, effect especially the straightness and rectangularity of the guide ways and scales. Temperature fluctuations that happen over time lead to different temperature levels in the machine structure since various structural elements have different thermal inertias. The different reacting times of the components to a new temperature level can cause different thermal expansions of the scale mounted to the ram of a bridge type CMM in the Z-direction and of the scales in the X- and Y-directions.

Deviations from the reference temperature of 20°C (68°F) [5,57] results in length variations of the CMM scales and of the workpiece. Due to the fact that the scales and the workpiece have different coefficients of thermal

expansion, a correct measured result is only guaranteed when the measurements are carried out at the reference temperature. When the actual temperature differs from the reference temperature, correct measurements can only be done when the three scales and the workpiece have the same temperature and their coefficients of thermal expansion are exactly the same, which is practically never the case.

The effect of thermal expansion can be corrected arithmetically. The arithmetic correction can be only as good as it is possible to determine the exact temperature and to possess the exact knowledge of the coefficient of thermal expansion for the scales and the workpiece under the condition of uniform temperature distribution. The value of the correction K and its uncertainty dK can be calculated as follows [57]:

$$K = l_0 * [\alpha_s * (T_s - T_r) - \alpha_w * (T_w - T_r)] \quad (3.1)$$

$$dK = |l_0 * dT_s * \alpha_s| + |l_0 * dT_w * \alpha_w| + |l_0 * (T_s - T_r) * d\alpha_s| + |l_0 * (T_w - T_r) * d\alpha_w| \quad (3.2)$$

where:

- l_0 = Reference Length
- α_s = Coefficient of Thermal Expansion for the Scale
- α_w = Coefficient of Thermal Expansion for the Workpiece
- T_r = Reference Temperature (20°C)
- T_s = Temperature of the Scale
- T_w = Temperature of the Workpiece

Vibrations, whether mechanical or airborne, influence the CMM performance greatly. Mechanical vibrations caused by external forces, like surrounding machines, lift trucks, compressors, etc., are transmitted via the support surface to the machine and can result in relative motion of the different machine components. This motion can be in the form of continuous vibrations, or interrupted shocks or both, and they may result in excessive deviations during measurement. Vibrations lead to stimulation of natural or forced oscillations of the machine and its subassemblies [57], and certain high amplitudes of shocks can even lead to damage of the machine. Airborne vibrations in the form of pressure waves, i.e. noise waves, may acoustically couple to the machine and may result in dimensional measuring deviations. Mechanical vibrations transmitted via the foundation or the floor can be prevented by selecting a proper location or by using shock-absorbing base elements. The CMM manufacturer usually specifies maximum vibration levels for the user (see Appendix A) and it is the user's responsibility to undertake the necessary vibration analysis so as to get all the required information for vibration absorbing arrangements.

Airborne Particles like dirt, dust, oil, grease etc. may effect machine performance and result in accelerated wear of the machine and its subassemblies. If operated in a dry dusty environment, air-bearing equipped machines can operate without adverse effect on performance because of their self-cleaning capability. If wet dust and dirt deposits in the guide ways, the bearing's streaming out air cannot clean them and this results in wear of the bearings and guide ways which can further effect the machine's long-term performance. Airborne particles may also deposit on the scales if they are not properly shielded. This can result in misreading of the position and also to reduction of the gap between the scale and the encoder, which further leads

to wear and damage of the optical measuring transducers. Although no formal standard for airborne particles exists, special attention during selection of the appropriate machine type should be taken and also preventive maintenance should be scheduled to clean the guide ways along with the scales and encoders regularly. Moisture, in the form of humidity, can also degrade machine performance by swelling up the machine table and guide ways if they are made of granite and this moisture may also result in corrosion of other subassemblies, especially the electronic machine components can be effected. Limit values for the relative humidity are therefore specified by the manufacturer and they should be strictly followed by the user.

4.3.2 Machine Specific Factors

Beside the various environmental factors, machine deficiencies degrade its performance. A very critical factor is the deviation of the machine's reference coordinate system from a mathematically ideal coordinate system. This deviation may be caused by deficiencies in the form and the orientation of the guides and the guide ways and may result from the fact that the movable subassemblies execute translational movements perpendicular to the traversing direction and rotational movements with a low angle of rotation [57]. Furthermore, the traversing directions of the moving subassemblies are non-orthogonal along the coordinate axes. The influence on the machine performance of these deficiencies is dependent, amongst other things, upon the machine configuration and it can vary greatly from position to position within the CMM's work envelope. Together with the deficiencies of the

measuring systems, deficiencies of the guides may also result in positional deviations, i.e. deviations of the output position from the actual position in the direction of the traversing axis. These deviations can result from deficiencies in the manufacturing of the scales. The positional deviations are dependent, in particular, upon the magnitude of the rotatory deviations and upon the Abbe offset [57]. The Abbe offset, which is the perpendicular distance between the measuring line and the measuring system, is named after Ernst Abbe (1893) who stated the Abbe's principle of comparison. This principle states that in order to keep the effects of deficiencies in guides as small as possible, the measuring line at the object should be aligned with the measuring system in one straight line. A CMM is not designed according to this principle and therefore an error, the Abbe error, may lead to positional deviations. However its effect can be reduced by use of extremely precise guides and guide ways. In addition, with today's computer capabilities, arithmetic corrections of the reference coordinate system can be made easily. These arithmetic corrections in the reference coordinate system, are also known as CAA or Computer Aided Accuracy and are done by measuring the motion of the CMM along its axes. These measurements are usually done using a Laser Interferometer with a certain step width within the whole work envelope and the measurement results are then stored in the machine's computer so that each measured point can be corrected according to an ideal reference coordinate system.

Deformations and natural oscillations of the machine structure caused by large acceleration and deceleration forces, effect the accuracy and may also result in measuring deviations. Deviations may also be caused by the probe system and are dependent on the type of probe system used, along with its electrical and kinetic characteristics. When using a contact probe system,

the used stylus adds uncertainty even after an accurate calibration, due to the probe pin deflection and deformation of the contact element caused by the probing force.

The CMM software is a very critical component in the overall machine performance. The European Community conducted several CMM software tests in the mid 1980s to investigate the influence of the various software packages on the measuring results. The investigations were realized by using generated data sets for each geometric element. The results of the element evaluation with the various software packages were then compared to a reference software. The outcome of the first test showed that there were tremendous deviations between different software when using the same data sets. Some software packages showed a calculation error that was larger than the measuring uncertainty of the CMM itself. A second test carried out in the years 1985 and 1986, showed that the software of the manufacturers had improved but deviations were still existing [17].

4.3.3 Operation Specific Factors

The third category of performance degrading factors are deficiencies during the operation of the CMM. The electrical power supply of the machine is subject to changes in voltage and frequency, that can influence the accurate machine performance and repeatability. This is particularly true when the machine is computer numeric controlled. If a CMM is equipped with air bearings, the air supply to the machine can degrade performance and decrease the useful lifetime of the machine. Temperature variations in the air supply can generate thermal gradients in the machine, whereas humidity can lead to swelling of the granite guide ways or cause corrosion. Therefore

dehumidifiers are installed to dry the air before it enters the air bearings. Oil, water and other particles in the air increase friction and accelerate wear which effects the long-time performance of a CMM. Both electrical power and limit values of the air supply need to be specified by the manufacturer so that the user can make necessary arrangements at the installation site.

The actual mass of a workpiece itself can lead to deformations of the table and the guide ways which can result in measuring deviations. Mass limitations for the machine provided by the manufacturer, should be observed strictly to guarantee proper performance and to avoid permanent damage. Besides the mass, other workpiece characteristics like surface roughness, form or hardness etc., may influence the measurement and should be carefully considered during the measurement preparation. In the case of soft materials like clay, wax or plastics, the local surface may elastically or even plastically deform due to high values of 'Herzian Stress' that is caused by the probing force. Therefore the probing force of the probe system should be adjustable or if the material is sensitive and the limit of the contact probe system is reached, the use of non-contact probe systems should be considered. Expected form variations of the surface should also be considered when choosing the size of the contact element. As shown in Figure 4.4, this can have some influence on the measuring results.

Furthermore, the operator is a source of uncertainty in various ways. The operator represents a source of thermal energy and transmits energy by radiation and by physical contact with the object being measured or with the subassemblies of the CMM. This influence can cause temperature gradients in the machine and is especially critical for manual driven machines where the operator has to touch the subassemblies to operate the machine. The operator or the measurement planner, if a special department for planning

the measuring tasks exists, also influences the performance by analyzing the measuring task, by choosing stylus configurations, probing forces and probing directions, by creating the part coordinate system, by deciding on a specific approximation method, etc. The measuring strategy can especially have great influence on measuring results. To keep influences through the operator as small as possible, the operator should be aware of all possible performance degrading sources together with an excellent training. The operators also should be tested on their performance, like the machine, on a regular basis.

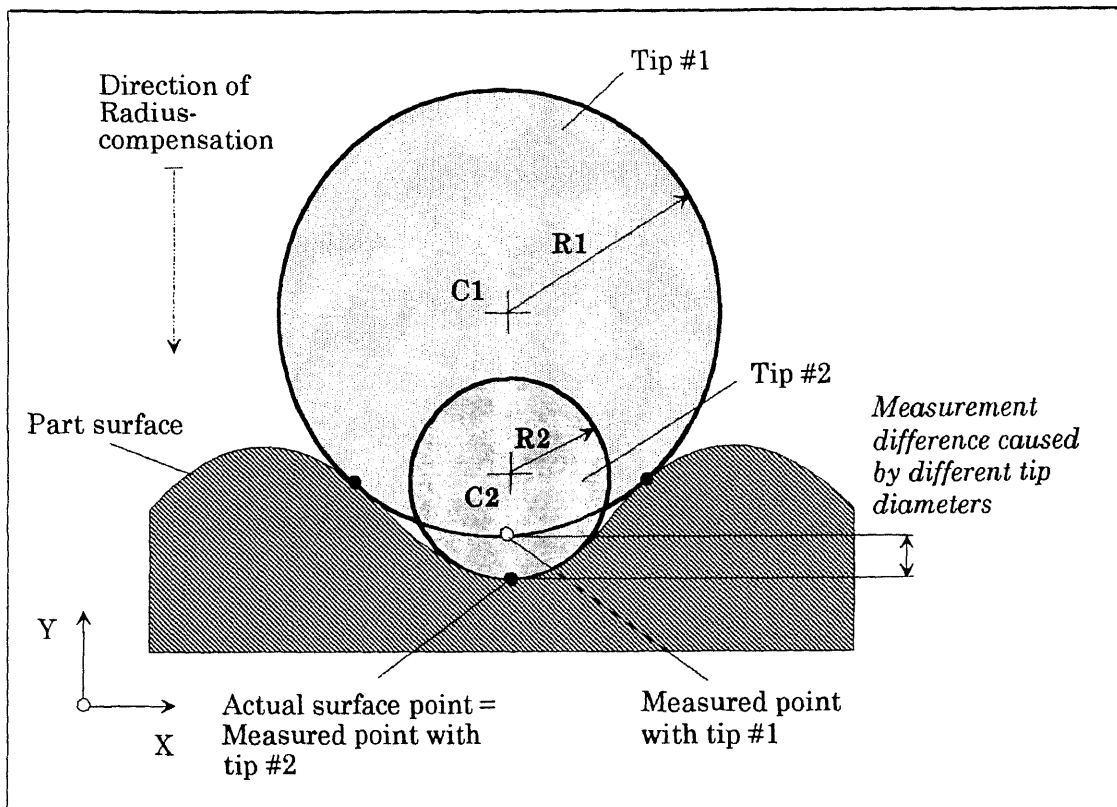


Figure 4.4 Influence of the Tip Diameter on the Measuring Results

4.4 Characteristics for Accuracy

As mentioned previously, the vector of measuring deviation cannot be determined over the entire measuring envelope due to the fact that no suitable measuring method is available. Therefore other methods must be used to describe the accuracy of a CMM. As described in [57], two basic approaches are possible:

1. *Describing the accuracy by components of the measuring deviation of the Coordinate Measuring Machine.*
2. *Describing the accuracy by the measuring uncertainty of conducted measurements.*

The first procedure investigates the effects of machine specific deficiencies by determining the individual components of the measurement deviation. The components of the measurement deviation are as follows:

- *Positional deviations*
- *Deviations from straightness*
- *Rotatory deviations*
- *Squareness deviations*
- *Probing*

Superimposing the individual measurement vectors of these components by vector addition is an extremely complex process which requires precise measurements of all components for the entire work envelope. Furthermore, the components are partially interdependent due to the static and dynamic flexibility of the machine and may also be influenced by parameters like loading or traversing speed. Owing to the extremely long

time it takes to determine the parameters of the individual components, the measurements are only done for selected measured lines within the measuring range. The individual components of the measuring deviation provide a good insight into the operability of the CMM subassemblies. However, it is not possible to calculate the measurement deviation anticipated for a specific measuring task or the applicable uncertainty of the measurement on the basis of the components [57].

The second procedure investigates the accuracy of a CMM by experimentally determining the measurement deviation by measuring test parts whose dimensions are known with exact certainty. Suitable test parts are calibrated gage blocks, stepped gage blocks, spheres, ring gages, etc. The measurement uncertainties for specific measuring tasks like length, circle or sphere measurement uncertainty may be specified so that all the CMM measurement deviations are taken into account as a total. This way of investigating the CMM accuracy provides information concerning a certain machine's suitability to specific measuring tasks and permits qualitative conclusions to be drawn in regard to other measuring tasks. This approach further allows comparison of the performance of CMMs of different manufacturers in a very easy way.

4.5 Performance Tests

Today CMMs are being used more and more for process control and for continuous improvement. It is therefore critical that the manufacturer know whether variability results from a change in the production process or from the inspection. The ambiguity of CMM performance specifications and wild claims about machine accuracy since the late 1960s made it necessary to establish a recognized standard to evaluate CMM performance. For this reason in 1978, the ASME B89.1.12 (The American Society of Mechanical Engineers) working group was established to work on a standard which would simplify and clarify the performance specifications. At the same time the international Coordinate Measuring Machine Association (CMMA) was founded in Europe with the same chief objective. Early attempts were made to coordinate the activities of both the groups to create a world standard, but little progress was made. Therefore the B89 group decided in 1980 to work independent of the Europeans. In 1983, the group proposed an interim standard and in 1985 the first version was published. In 1990, the current second, improved version, the B89.1.12M-1990 [5] standard was published. In 1986, the German Association of Engineers (VDI Verband Deutscher Ingenieure) and the German Association of Electrical-Engineers (VDE Verband Deutscher Elektrotechniker) published a guideline for the accuracy of CMMs, the VDI/VDE-Richtlinie 2617 [57,58,59,60,61]. In many other countries different standards for CMM performance testing are established which may differ greatly from each other. For this reason, to compare CMM performance on an international level an ISO (International Standard Organization) working group TC 3 WG 10 [34] is currently trying to establish an international recognized standard. From today's point of view the future

international standard will employ gage blocks and stepped gages as test parts to evaluate CMM performance, like most of the other current national standards.

In the following sections, the US-standard B89.1.12M-1990 and the German specification VDI/VDE-Richtlinie 2617 are viewed against each other. A clear comparison between these two standards is not possible because of their widespread differences. Even when some test procedures seem alike, a major difference can result from the evaluation procedure of the test results. The values characterizing the machine performance in the two standards are not equivalent.

4.5.1 The B89.1.12M-1990 Standard

The B89.1.12M-1990 standard consists of seven parts, which are further complemented by nine appendices. The parts in which the standard is structured are:

1. *Scope*
2. *Definitions*
3. *Environmental Specifications*
4. *Environmental Tests*
5. *Machine Performance*
6. *Subsystem Performance Tests*
7. *Test Equipment*

The purpose of this standard is to define the simplest testing methods for the majority of CMMs. It is not intended, as stated in the standard, to

replace more complete tests that may be required for special applications. It is applicable for rectilinear CMMs, with three linear axes and up to one rotary axis, employed with contact probe systems used in the point-to-point probe mode rather than in the scanning mode. Non-contact probe systems are not covered. For evaluating the test results, the concept of range ($|\text{Max.} - \text{Min.}|$) is used throughout the standard as a measure of the machine performance.

The second part defines terms used in the standard and also defines ten common machine classifications. The parts starting from part 3 to part 6 form the actual standard. These sections cover environmental influences on machine performance and the test procedures (Part 3 and Part 4), the actual machine performance testing methods (Part 5) and a subsystem performance test (Part 6) which analyses errors caused by a contact probe system in the point-to-point mode.

Part 3 of the standard clarifies the effects of environmental parameters on the machine's accuracy and repeatability and also provides environmental specifications for using and testing CMMs. The four major environmental problem areas addressed by the standard are: *temperature, vibration, electrical and utility air*. The base temperature for measurements is 20°C (68°F) which is in accordance with the international specification of length. The overall responsibility to provide an adequate environment according to this standard is given to the user. Appropriate environmental tests are given in Part 4 and they are complemented with the appendices B, C, D and E. If the environmental specifications cannot be met by the user, the standard provides a formula which allows the CMM manufacturer to degrade the machine performance by increasing the working tolerance.

Part 5 is the actual machine performance section of the standard which expands on the testing of the CMM as a whole system. It consists of five major parts :

- Hysteresis test
- Repeatability test
- Linear displacement accuracy test
- Volumetric performance test
- Bi-directional length measurement capability test.

The mechanical *hysteresis test* is strongly recommended to be performed on the machine and on any test setup before further tests are made. In Appendix 7 of the standard further information about designing the test are given. Problems encountered in the hysteresis tests should be corrected before investigations on machine performance are continued. Any excessive hysteresis which is not corrected would most likely lead to a lack in repeatability of the other tests.

The *repeatability* is defined in the scope of B89.1.12M as "a measure of the ability of the instrument to produce the same indication when sequentially sensing the same quantity under similar measurement conditions." The repeatability test is done by repetitively measuring the center position of a highly precise test sphere that is rigidly mounted on the worktable. The repeatability is tested under normal operation conditions and as the characteristic of repeatability the range of the center positions is evaluated.

The linear displacement accuracy test provides traceability to the international standard of length and is performed either by using a step gage or a laser interferometer. Its purpose is to check the scales' calibration which forms the machine's reference coordinate system. The test is done for three orthogonal measuring lines at the center of the work envelope parallel to the three axes of travel. The linear displacement accuracy as a result is reported for each axis as the maximum range of the mean differences between the calibrated steps and the machine readings. If a laser interferometer is employed instead of a step gage, the linear displacement accuracy is reported as the maximum spread of the mean differences of all measured positions.

The volumetric performance test or the ball bar test evaluates the machine's ability to allow consistent measurements of an uncalibrated length in various specified positions within the work zone. The purpose of this test is to provide a simple checking procedure to investigate geometric imperfections of the CMM such as out-of-squareness or error in angularity. In accordance with the attempt of the B89.1.12M standard to reduce time and cost associated with CMM testing procedures an uncalibrated artifact, the ball bar, is used for testing. The ball bar consists of a rigid rod with two highly precise spheres attached to its ends. A design recommendation for the ball bar and mounting sockets is given in the appendix G of B89.1.12M. The standard further allows the ball bar to be replaced by a gage block of the same length which gives additional information about the machine performance. The volumetric performance test is seen as an extremely useful quick acceptance test procedure which rechecks the machine's overall measurement ability on a periodic basis. As the standard points out very clearly, the ball bar test is used in conjunction with the linear displacement

accuracy test. The machine accuracy cannot be solely based on the test results of the ball bar test. As a result of the ball bar test the performance characteristic "working tolerance", is evaluated by the range of the ball bar lengths measured in all the specified positions.

In addition to the general volumetric performance test using a vertical probe, a performance test in four positions with an offset probe is also carried out. The purpose of this test procedure is to evaluate the effect of angular ram axis motions by determining the machine performance when offset probes are used. The length measurements of the ball bar are done under normal conditions in two probe offset positions, in which the second offset position is rotated by 180 degrees from the first. The offset probe performance characteristic is reported as the ratio of the difference in ball bar length in the two positions to double the amount of the probe offset length.

The third volumetric performance test described in the standard applies to machines with a rotary axis. The test employs two precise spheres which are rigidly mounted to the rotary table at different heights. The spheres are being measured in fourteen different nominal angular positions that are specified in the standard. The working tolerance for a rotary axis is specified by two characteristics: *the four-axis working tolerance and the 3D/alpha working tolerance*. The first characteristic is determined by measuring the center distances between the two spheres on the rotary table. It is calculated as the range of the deviations from the nominal distance of the two spheres divided by the nominal distance. The 3D/alpha working tolerance uses the same measurement data but analyses the X, Y and Z center positions of the spheres. The maximum range of the three center coordinates of the two spheres divided by the distance of their corresponding

center coordinates to the rotary axis are defined as the 3D/alpha radial performance, 3D/alpha tangential performance and 3D/alpha axial performance.

The *bi-directional length measurement capability test* investigates the probe calibration error or probe and machine hysteresis by analyzing two-sided length measurements. The testing procedure is carried out for four measuring lines by measuring a gage block under normal conditions. The largest deviation of the measured value from the gage block's calibrated length is defined as the bi-directional length measurement capability.

Part 6 of the B89.1.12M standard describes a subsystem performance test which carries out the performance analysis of the probe system in the point-to-point probing mode. The probing system performance contributes very much to the overall performance of the whole CMM system. The purpose of this testing procedure is to investigate the magnitude of the error contributed by the probing system. The probe, the probe stylus, probing parameters, like probe approach rate or probe approach distance, the machine dynamics, etc. can be listed as parameters effecting the performance. The test is carried out for three different stylus configurations by measuring a precision sphere under normal operation conditions. The sphere is being measured on four different heights with 12 points each and one point at the pole for a total of forty-nine points. For analyzing the point data, a sphere is calculated with all the 49 points. The point-to-point performance characteristic is defined for each stylus configuration as the range of the radii from the center of the sphere to each of the 49 measured points. Furthermore, an optional probe approach test is described in which the approach parameter, probe approach distance and probe approach rate

are varied in order to see their influence on the probing system performance. The test procedure is similar to the one described above.

Part 7 of the standard specifies the necessary test equipment needed for test procedures and is followed by the appendices that provided additional information concerning the test procedures.

4.5.2 The VDI/VDE-Richtlinie 2617

The VDI/VDE-Richtlinie 2617 is an industry guideline published by the German association of engineers and the association of electrical engineers and consists presently of five individually published parts. Each part of the guideline covers a certain accuracy problem area of CMMs in detail. The parts in which the standard is structured are:

- *Generalities (Part 1), Apr. 1986*
- *Length Measurement Uncertainty (Part 2.1), Dec. 1986*
- *Components of Measurement Deviation of the Machine (Part 3), May 1989*
- *Rotary Tables on Coordinate Measuring Machines (Part 4), Sep. 1989*
- *Supervision by mechanical Standards (Part 5), Aug. 1991*

Additional parts for measurement task specific uncertainties like circle and sphere measurement uncertainty will be published under part 2 of the guideline at a later date. Other supplementary parts for performance analysis of CMMs dealing with scanning, optical CMMs and software are to be published also.

The purpose of the guideline is to define characteristic parameters for the accuracy of CMMs and to define suitable checking methods for these specifications. Using mechanical or electromechanical contact probe systems, the guideline is applicable to rectilinear CMMs with three linear axes and a rotary table, for measuring robots and for one- or two-dimensional CMMs when simplified according to the guideline. This guideline also requires a mechanical or electromechanical contact probing system. Non-contact probing systems are not covered. The testing methods are to be only considered as sampling inspections since a 100%-inspection of the machine at all points of the working zone is not possible. The test results therefore are treated in statistical manner.

Part 1 of the guideline provides general information about accuracy of a CMM and mentions in detail diverse accuracy influences to be considered when measuring with a CMM. In this part, operating and ambient conditions are given as an example. Environmental testing procedures similar to the US standard B89-1.12M-1990 are not purposed in this standard because for all test procedures it is assumed that the environmental guidelines are met by the user. Consequently, formulas which would allow degradation of the machine performance if ambient conditions are not met by the user, are not given.

Part 2 of the guideline deals with measurement task specific measurement uncertainty to allow comparison of CMMs of different configuration and different levels of automation. So far only section 2.1 "The Length Measurement Uncertainty" is published. The length measurement uncertainty is defined as "the measurement uncertainty of the distance between two points lying on opposing parallel surfaces" and it is valid for bi-directional as well as for unidirectional measurements. The length

measurement uncertainty is specified in the VDI/VDE-guideline 2617 as the length-dependent parameter "u".

$$u = A + K * L \leq B \quad (4.1)$$

where:

- u = Length measurement uncertainty
- A = Constant for length independent factors
- K = Constant for length dependent factors
- L = Measured length
- B = Limit value for u specified by the manufacturer

For the specified test equipment, gage blocks of various lengths, a step gage block or a laser interferometer can be employed for testing the length measurement uncertainty. Depending on the space direction in which the lengths are measured a one-, two-, or three-dimensional length measurement uncertainty is distinguished. The one-dimensional (1D) length measurement uncertainty is determined when the test lengths are directed in the direction of the axes of travel. The two-dimensional (2D) length measurement uncertainty is determined when the lengths are directed in a 45 degree angle to the axes of travel and the three-dimensional (3D) uncertainty when directed with an azimuth of 45 degree and an elevation of 35 degree. Depending on which test equipment is being used, five or ten lengths are measured five or ten times with a short straight stylus of high rigidity under normal conditions. As a result of the test, the length measurement deviation (ΔL) between the calibrated and the measured length of the gage block is evaluated. When a laser interferometer is employed as the test equipment, ΔL is evaluated by the measurement deviation of the length indicated by the

laser interferometer and the coordinate readings from the CMM. Due to different test equipment, the results obtained may differ from each other therefore the kind of test equipment being used has to be specified on each inspection report. The acceptance inspection report consists of seven measurement uncertainty diagrams (1D-, 2D-, 3D-length measurement uncertainty) like the one shown in Appendix B. If 95% of the test results for each test fall in between the area of acceptance, the CMM complies with the manufacturer's specification of CMM length measurement uncertainty.

Part 3 of the VDI/VDE-guideline is aimed at investigating the different components of measurement uncertainty as described in section 4.4. As previously mentioned deviations of the ideal reference coordinate system and the measurement deviations of the probe system are very critical to the overall performance of the CMM. Part 3 therefore defines the characteristic parameters and proposes test procedures for each component to allow insight into the operating ability and capability of the CMM. All the test procedures are carried out under normal operating condition. The test procedures and evaluation procedures are described in short below. As an example, an acceptance test report for each component is provided in Appendix B as additional information. For detailed information however the interested reader should refer to the VDI/VDE-guideline itself.

The *positional accuracy* of a CMM can be defined as the ability to move to and return repeatedly to a specified position within the working range. The positional accuracy is determined by comparing the indicated position of the CMM with the position indicated by an external measuring device, like a laser interferometer or a scale with a reading microscope. Out of eleven positions for each axes of travel, the CMM has to be positioned at least five

times in the positive and the negative axis-direction. The evaluation of the positional accuracy can be done with two different evaluation procedures that are described in the guideline. The first procedure follows the statistical method in which the parameters position uncertainty, position deviation, reversal span and position spread are evaluated for each axis direction. The second method uses a position uncertainty template which is specified by the CMM manufacturer. The template is placed over the measurement deviation diagram of the same scale as the template to check if the specified position accuracy is fulfilled (see appendix B).

The straightness can be defined as the deviation of a reference point's line of motion along an axis of travel from an ideal line. The specified test employs a straight-edge standard or a laser interferometer as test equipment and is carried out for each axis direction by measuring the straight-edge of the standard in the positive and negative axis direction. The straightness is evaluated from the straightness deviation diagram as the ordinate distance between two straight lines which enclose all the measured deviations (see appendix B).

The squareness can be defined as the angular deviation of two perpendicularly directed axes of travel from a square. It is tested by using a mechanical square or by a laser-optical measuring device. When two lines of a mechanical square are measured for the straightness, best fitting measuring lines can be determined by the least square approximation method. The squareness for each coordinate plane is determined as the angular deviation from 90 degrees of the measured lines, while taking into consideration that the mechanical square is not an ideal square (see appendix B).

Rotary movements can be carried out by the subassemblies of a CMM when traversing in the axes of travel (Figure 4.5). Rotational angles, also known as the roll, pitch and yaw angle of an axis generally cause linear measurement deviations as the distance from the scales increases. For an ideal CMM the rotational angles for each axis is equal to zero. The test methods for the different angles in each axis direction described in the guideline are numerous. The interested reader should refer to the guideline itself. The test procedure is carried out for each axis direction, for the entire working range in the positive and the negative traversing direction, at a measuring line located approximately at the center of its spatial measurement range. For evaluation of the rotational angles the rotational angle deviations are plotted for the positive and negative traversing direction in a diagram, where the maximum rotational angle is determined as the ordinate distance between two parallel lines to the abscissa which encloses the measured lines (see appendix B).

The probing uncertainty is determined for the same reasons as described in the B89.1.12M-1990 US-standard. The VDI/VDE-Richtlinie 2617 however distinguishes between a 1D, 2D, 3D-probing uncertainty and differs in the test procedure in some points. For determining the 1D probing uncertainty a gage block or a gap gage is measured 50 times. It is evaluated as the distances from the arithmetic mean length so that 95% of the measurements have to be within the manufacturer's specifications. The 2D-probing uncertainty is determined in a similar way by measuring a ring gage 50 times. The 2D probing uncertainty is then determined as the distances from a least square fitted circle for 95% of time. The 3D-probing uncertainty is determined by measuring a precise sphere analogous to the previously described procedure and evaluated by the same method.

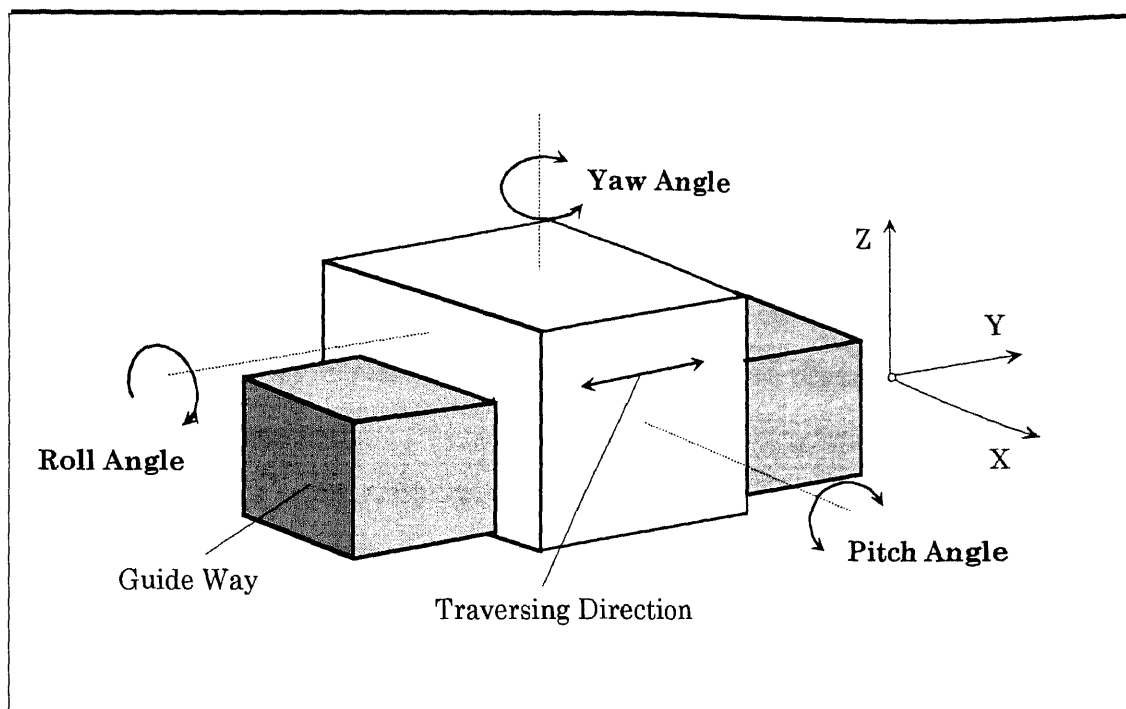


Figure 4.5 Rotational Angles of a Guide During Traversing

Part 4 of the guideline covers the influences on CMM performance when a rotary axis is used as a fourth axis. In general the accuracy of a CMM decreases with the use of a rotary axis because of its deviations from an ideal axis of rotation and the correct angle of rotation. Part 4 defines and describes test procedures for the different components of rotary table deviations, i.e. angular position deviation and deviations caused by axial and radial movements and by the wobbling of the axis of rotation. For more information about the single testing and evaluation procedures of the rotary table component test refer to the guideline. The components of rotary table deviations superimpose on the deviations of the three-axis CMM. Due to the rotary table deviations a displacement of the measured position from the actual position occurs that can be expressed as lengths in axial, radial and tangential direction. Mathematical relationships for each displacement direction are given to calculate the magnitude of the displacement depending

on the components of rotary table deviations. In order to test the interaction of an employed rotary table and the CMM a test procedure similar to the one described in the B89.1.12M-1990 US-standard determines the 3D/alpha measurement uncertainty for the axial, radial and tangential displacement directions. The evaluation method for the 3D/alpha measurement uncertainty however differs from the US-standard so that the results cannot be compared directly.

Part 5 of the VDI/VDE-Richtlinie 2617 defines simple, praxis oriented test procedures for testing the machine performance periodically. The CMM users should ensure the accurate performance of their machines in the manufacturer specified tolerance range. The entire CMM-system has to be tested on a regular basis that does not exceed a period of six months. The probe system performance should be checked on a weekly basis. The testing procedures therefore have to be designed to be easy and fast with low associated costs. When the testing parameters hold constant a trend analysis of the CMM performance can be drawn which enables the user to view changes and plan preventive maintenance for the CMM. The described test procedures in this part of the guideline investigate the probe system uncertainty and the three-dimensional measurement uncertainty by using calibrated artifacts.

For testing the probe system uncertainty a precise sphere or a ring gage is used. The test parts are measured with different stylus configurations. The range of the radius deviations of the measured points to the radius of mean element approximated by the least square method is determined to be the probe system uncertainty. The specified limit value for the probe system uncertainty has to be met for all measuring positions of the test part with any stylus.

For testing the *three-dimensional measurement uncertainty* either one, two or three dimensional calibrated artifacts are employed. The measurement uncertainty is measured bi-directionally with gage blocks of different lengths or a step gage block, as calibrated 1D artifacts, in at least three space diagonal directions within the entire work zone. For 2D artifacts, a calibrated space plate with regularly placed holes or spheres are measured in at least two crossed positions in a measurement plane tilted at an angle between 30 and 45 degrees to the coordinate plane (Figure 4.6). 3D artifacts, like calibrated hole blocks, are measured in only one position within the work zone if the size of the block is large enough to cover the entire work zone. If this is not the case, the block has to be measured in different locations of the work zone.

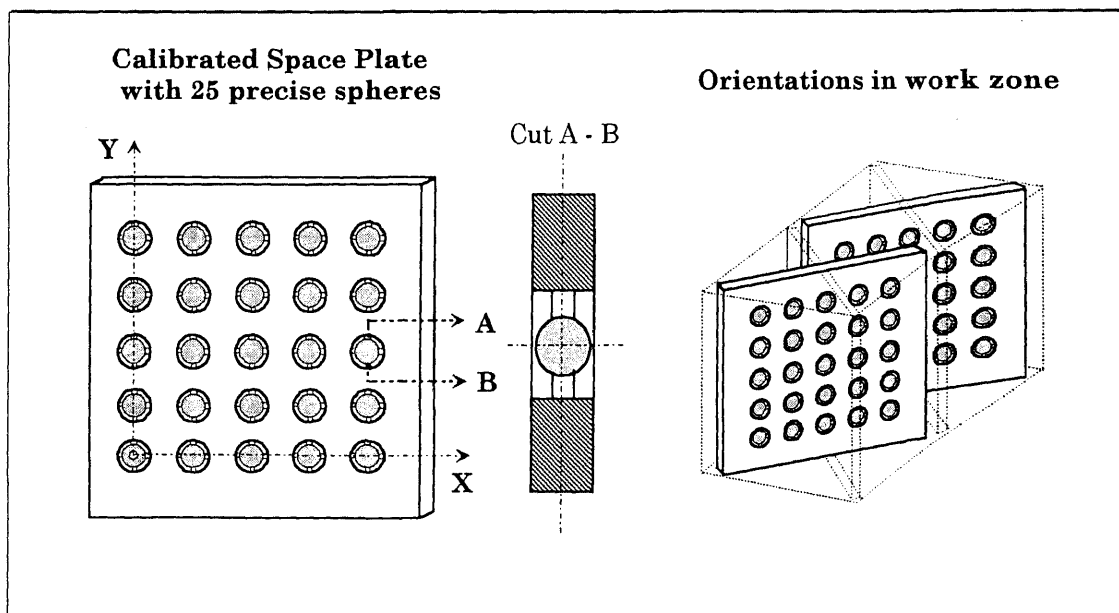


Figure 4.6 Space Plate Design and Measurement Orientation in Work Zone

The tests are carried out by using a 1D, 2D or 3D artifact under normal operation conditions with frequently used styli configurations. For evaluation of the measurement uncertainty the difference between the calibrated lengths and the measured lengths of the artifact are plotted in a measurement uncertainty diagram independent of the space direction of the measured length. The three-dimensional measurement uncertainty limits can be calculated according to part 2.1 of the guideline using the following linear equation.

$$u = A + K * L \quad (4.2)$$

The length independent parameter A and the length dependent parameter K are specified by the manufacturer after the first test run of the CMM at the customer site. After each new calibration of the machine the parameters A and K have to be specified again. The machine is tested as "in specification" when all the measuring points are in between the limits.

CHAPTER 5

PROGRAMMING OF COORDINATE MEASURING MACHINES

5.1 Programming Methods

Increasing competition, shorter lead-times, higher quality standards and the pressure to react very fast to demand and design changes make high demand on dimensional metrology in today's industry. Modern computer controlled Coordinate Measuring Machines represent a flexible inspection tool with the capabilities to respond to these demands. Traditionally, the measurement preparation for a CMM required a lot of time with the majority of time consumed in programming the machine. Therefore, evolution effort was put into the development of ways which would reduce programming time and allow data exchangeability with a CAD database. Looking at today's CMM market, the CMM manufacturers offer their users two fundamentally different ways of programming their DCC-CMMs:

- *On-line Teach-in Programming*
- *Off-line Remote Programming*

On-line Teach-in Programming is the traditional and the most common way of programming a DCC-CMM. The CMM is connected on-line via the machine controller to the computer where the program code is entered to measure the required object attributes specified in the measurement request. The programming process is concise with a manual measurement for the particular measuring object. The probing and clearance points for each geometric element and the clearance points in between the elements are

individually determined, to lead the probe system collision-free around the part, using the control box to drive the axes. Nominal values and tolerances are keyed into the computer keyboard to enable the software to make comparisons between the actual and the nominal. After testing the program for errors and collisions, the measurement program can be used with the same stylus configuration and relative alignment in the work zone for multiple measurements of similar parts. The part program can also be used on a different CMM of the same type with the same configuration and software. The main disadvantage of this kind of programming is that it requires a lot of time during which the CMM cannot be used for productive measurements. The main measurement time for CMMs employing teach-in programming is therefore logically less, which has to be considered during the economic analysis of the CMM's purchase. In order to overcome this main disadvantage, the CMM manufacturers sought off-line programming methods which would allow programming the machine without physical use of the machine.

Off-line Remote Programming of CMMs does not require the CMM itself for data input during programming. It can be realized in basically two different ways presently:

- *Off-line programming from a special CMM programmer work place*
- *Off-line programming with data connection to a CAD-database*

In the first method a CMM programmer writes the measurement program and enters all the necessary information and the machine control data via the keyboard or a digitizer. The programming systems available for remote programming are either manufacturer specific or manufacturer

independent. The manufacturer specific programming systems are dialog oriented program packages which run under a similar computer environment as the CMM software of the specific manufacturer. The program code employed is usually the same as the code for programming the machine on-line. These systems are very often supported by graphical simulation software packages which enable a simulated test to be run on the computer screen after the measurement program is completed. This way errors and missing points can be detected and corrected before the program is finally tested on the CMM itself. An example of a manufacturer independent programming system is the problem oriented programming language N.C.M.E.S. (Numerical Controlled Measuring and Evaluation System). N.C.M.E.S. uses a manufacturer neutral code and data format to write the measurement programs. After completing the measurement program, the program is adjusted for the specific CMM before it is downloaded using a post processor that generates the CMM specific machine code. The language N.C.M.E.S. is based on the EXAPT language which is a popular NC-programming language in manufacturing systems. This was done so that it would be easier to integrate the new language with existing systems in the manufacturing environment. Most of the commands are similar except the machining commands are replaced by measurement specific commands. Extensive calculation and generation programs with separate geometric and technology data processing are added to guarantee a maximum user support. Like the manufacturer specific systems, the program code and the geometric and machine control data are keyed in via dialog oriented input masks. In addition a graphical simulation package allows a visual collision test before post processing the program. Despite the efforts to develop remote CMM programmer work places, they are not very popular because the programmer

requires some spatial imagination to determine the machine control data from a two dimensional blueprint. Following the idea of integrated systems which make use of data from a common database, CAD/CAM systems were developed for sharing data in production. The same system integrity which was reached for production becomes a reality when a CMM programming system is connected to a CAD-database from which the geometric and machine control data can be retrieved. The CAD-database connection serves two primary functions:

- *Programming of a CMM from a graphical, interactive CAD/CAM programming work place*
- *Data exchange of geometric nominal data and measurement results between the CMM and the CAD/CAM programming work place, for basic geometric elements and contoured surfaces*

An important prerequisite is that the CAD-database be capable of storing the entire topology of an object as well as the technological data and be able to interrelate the data. The nominal data needed for programming a CMM is retrieved from the database and transmitted via a standard interface (IGES, DMIS, VDAFS,...) to the CMM programmer's CAD/CAM work place. The CMM programmer selects the object elements of interest, determines the stylus configuration needed to measure the selected features, defines the elements for aligning the part and also adds additional information or corrects errors if necessary. After completing the measuring program a simulated test run evaluates the program on errors and collisions before it is post processed for downloading into the machine. For bi-directional data exchange the measuring results are stored in an output file format similar to

the input file which can be uploaded into an operational database, so that they can be used by other integrated computer systems like a CAQ-system.

The CAD-database connection however opens up another technological possibility known as reverse engineering. Reverse engineering extracts the topology data of an existing object by measuring sufficient surface points to describe the entire object topology in a mathematical form on a CAD-system. There are numerous applications for reverse engineering capable systems, for example to create new drawings of broken or worn-out parts where no original drawings exist. These engineering systems are heavily used in the automobile industry where car bodies are styled by a designer based on esthetics rather than on mathematical models. By scanning small scale car models on a CMM, the topology can be processed in a CAD-system from where data can be used to manufacture stamp press dies. Reverse engineering also allows extraction of dimensional data of a competitor's product of which no drawings are accessible.

5.2 Program Planning

Dimensional inspection of parts and subassemblies costs money which can contribute tremendously to the total cost of a product. To keep inspection costs low and to ensure exact and reliable test results, it is of extreme importance to have the measurement process effectively planned. The inspection request, where the inspection features are specified, the blueprint and the physical part itself (if it already exists) are utilized for the measurement task analysis, which is the first step in the measurement planning process. The measurement task analysis defines the necessary

geometric elements and the sequence in which they are measured so that inspection data can either be directly obtained from them or through calculations. For instance in the case of determining a part edge that cannot be measured by a contact probe system, it can instead be calculated as the intersection line of the elements which form the edge, which may be two planes. The output of the analysis should be a measuring strategy with which the task can be solved. For developing the measuring strategy a strong knowledge about coordinate measuring technique, geometry and the machine's capabilities are required of the CMM programmer to get accurate results. If the measuring strategy is inadequate for solving the task the results turn out incorrect.

Element names become important during the analysis especially when the measurement task is extensive and so the possibility of losing the overview of the elements and how they were created exists. From experience it is known that establishing a commonly agreed upon code system to name the measured and calculated elements is of great help and it eases the search for errors at a later time.

The next step in the planning process involves deciding upon the geometric features for creating the part coordinate system. This step is of great importance for the entire measuring process and for the obtained data and therefore should be done very carefully. Depending upon the functional needs the most accurate geometric features should be used when applicable. For instance to determine the runout of a camshaft, the bearing locations should be used as the reference to create the coordinate system, since other features in this particular context are pointless.

After all the elements that have to be measured in order to solve the entire measurement task are determined, the relative measurement location

and the orientation of the part along with the stylus configuration are decided upon. If no automatic stylus change system is installed on the CMM, the stylus configuration requires attention during the planning stage so as to allow the measurement to be carried out while staying at one part location. Theoretically a measurement in more than one location is possible, but this is not desirable since deficiencies in creating the part coordinate systems can result in an inaccurate translation vector which adds to the measuring uncertainty. In this step of the planning process decision has to be made regarding the use of a rotatory table. This can decrease the measuring time tremendously and can also effect the necessary stylus configuration. It should be pointed out again that the fourth axis added by the rotatory table will lead to more measurement uncertainty. For determining the part location in the work zone, the travel paths of the employed stylus configuration are considered to ensure that the CMM axes are not driven to their maximum positions. If the work zone is large enough, the location of two or more parts should be considered to allow the second part to be setup while the first is still being measured to decrease downtime. The exact stylus configuration with all the adapter elements, the shaft and ball sizes and the orientation of the stylus relative to the machine coordinate system, should be documented in addition to the relative part location and the part's orientation in the work zone.

In the next step decisions concerning the fixing process, the fixing equipment and the padding are made. The purpose of fixing the part in its predetermined location and orientation ensures that it is not displaced during the measurement by contact forces and by acceleration or deceleration forces while it is mounted on a moving table. The supporting points and fixing forces should be chosen carefully in order not to deform the part and

increase the measurement uncertainty. This is of special importance when long and thin parts are mounted. The fixing equipment, the padding and their locations should be documented in detail to avoid collisions with the stylus when the measuring program is reused at a later time.

At this stage in the planning process the setup and the programming process begins. Following the SMED method (Single Minute Exchange of Dies) to keep the downtime of a CMM as less as possible, the setup process can be divided into external and internal activities. External activities are activities which can be performed without the use of the CMM, unlike the internal activities for which the CMM is needed. While external activities are being performed other activities can be carried out. These activities include configuration of the stylus and pre-mounting of the workpiece on a mounting plate when such a plate is being used. This plate is then clamped with fast-clamping devices against a stop onto the machine table. If the CMM is programmed using the teach-in method, the program code and the nominal data can be prepared before the machine control data is entered into the machine. To decrease the downtime while teaching the travel path of the probe, off-line programming methods were developed. Through the use of off-line programming, internal activities are shifted to the external side to decrease CMM downtime. As internal activities stylus calibration and part alignment are carried out. The stylus calibration has to be done before the styli can be used for measuring. It is usually done by measuring a precise calibration sphere with known diameter. When the stylus makes contact, the shaft and the contact element get deformed by the contact force. The calibration calculates a correction value for each stylus to correct the effect of the deformations. If a ball is used as the contact element, a virtual ball diameter which is different from the physical diameter, is calculated to

correct the measurements later on. The first action of each measurement program is to establish the part coordinate system for mounting the part onto the CMM. Most of the time this will be done manually if the part location is not pre-determined. However, if the part can be positioned always in the same location by using stops the alignment process can be entered once and then executed automatically after that. After completing the measurement process the measured data is processed for further evaluation and documentation. If the data is transmitted to a different terminal than the one used for the CMM, data processing is performed as an external activity so that the CMM is available for other measuring operations.

5.3 Probing Strategy

The probing strategy is a very important part of the measuring strategy and is developed during the measuring task analysis. Someone who is inexperienced in coordinate measuring technique might incorrectly think that probing strategy has no impact on the measuring results. Researches have shown that the probing strategy can have great impact on the measurement uncertainty and on the results obtained. On one hand the probing strategy determines the necessary amount of points and their distribution over each geometric feature and on the other side the procedure to measure the points using a probe. The strategy therefore is either oriented towards the basic geometric features of a part or towards the whole part itself when contoured surfaces like car bodies or turbine blades are inspected. The goal of an effective probing strategy is to determine the number of probing points and their distribution in such a way that within a minimum of

measuring time by using a suitable approximation criteria, the results can be expected with a high degree of confidence within a predetermined confidence interval [19]. In coordinate measuring technique the measuring results are determined using a definite number of probing points. Therefore depending on the probing strategy the results deviate from their theoretical values which are determined using the entire surface. These deviations result in an unknown systematic measuring deviation. To ensure accurate measuring results the probing strategy has to be chosen in such a way that all the systematic and random deviations do not exceed a certain value of measurement uncertainty.

For a probing strategy the number of probing points and their distribution are determined keeping in consideration certain factors during the planning process [19] :

- *Type of geometric element (Circle, Plane, Cylinder, Circle, etc.)*
- *Size of the geometric element*
- *Completeness of the element (Circle / Circle segment, etc.)*
- *Nominal deviations and tolerances*
- *Function of the part under investigation*
- *Manufacturing process of the form elements*
- *Measuring device (Probe system, measurement uncertainty, etc.)*
- *Available measuring time*
- *Element characteristic to be determined (length, shape, location, etc.)*
- *Approximation criteria*
- *Confidence interval for the measuring results*
- *Purpose of the measuring results (SPC, error analysis, etc.)*

So far it was not possible to develop a mathematical model which would make it possible to analytically determine the optimal probing strategy using the previous mentioned factors of influence. When dealing with geometrically ideal elements, which is never the case in reality, the probing strategy has no influence on the results, no matter how many probing points are taken and how they are distributed and also which approximation criterion for evaluating the substitute element is used.

In [19] the influence of the probing strategy is shown for a theoretical example of a circle and a line. In the example of the line a sinusoidal surface shape with a known actual form deviation is assumed to be the actual part surface. A measuring length on which the measuring points (starting with three points) are equally distributed, is determined in such a way that the length is not a multiple of the frequency of the sinusoidal wave. Starting from a fixed position the measuring length with the points is shifted by a length Δx along the surface. In this manner the measuring points change their relative locations on the sinusoidal wave which changes the form deviations when they are evaluated with the Tschebyscheff minimum criterion required in the ISO 1101 standard. This procedure is continued with varying shift lengths and also varying number of points on the measuring length. The results of the investigation demonstrate that for a certain number of measuring points (independent of the relative point positions) the measuring result approaches a threshold value which is equal to the actual form deviation.

For developing an optimal probing strategy all influence factors are taken into consideration. If the systematic form deviations of the part surface are not known with a certain degree of confidence, the probing point density

should then be chosen as high as economically possible. The inexperienced user should be aware of the lack in measurement accuracy when only the mathematical minimum number of probing points are taken. Also, the metrological minimum number and their distribution pattern over the basic geometric elements that is recommended in many books is not much better. Most often this number of points just allows a form evaluation of the element. Due to the absence of an analytical model which would give the optimum number of probing points the number should be determined from experience while considering the influence factors. If the CMM is programmed with the teach-in method, the CMM-programmer has the physical part available to decide upon an optimal probing strategy. By looking at the results of the test run the programmer can make adjustments in the probing strategy if necessary. If the CMM is programmed off-line, the physical part very often does not exist which is especially the case when concurrent engineering is performed in a company. Therefore it is sometimes hard for the programmer to decide on the probing strategy because all the information available to him is in numerical form. Actual test results are first available after a part is measured so that corrective actions can be taken. In the future off-line programming of CMMs will become more important and will be performed by employees that may not be aware of all the characteristics of coordinate measuring technique and of the employed CMMs. For this reason programming software with access to an expert system should be developed which can support the user effectively in the future.

CHAPTER 6

PROSPECT OF CMM EVOLUTION

Coordinate Measuring Machines are universal measuring machines to which no single or particular measuring task is assigned. Almost every dimensional measuring task, starting with simple prismatic parts to complex free form shaped sheet metal parts, can be solved with a CMM if the appropriate machine configuration is available. This fact along with the implementation of a re-programmable computer unit, turns CMM into a flexible measuring device that meets the expectations of today's progressive industrial environment. Once a part inspection program is written and tested, it can then be repetitively used for dimensional inspection of the same part. Using software rather than hardware for the part alignment reduces the setup time, increases the accuracy and diminishes the operator's influence on the results as compared to the conventional surface-plate inspection techniques. Due to short inspection times and fast setups, the CMMs offer the capabilities to effectively close the quality loop in production by providing fast and accurate feedback data to control and improve the production process. All previously mentioned advantages and capabilities together are the reason why CMMs were introduced so fast and will further gain ground in industry in the future.

The future CMM evolution activities will mainly be concentrated in areas with goals to decrease measuring time, increase environmental resistance and allow a better data integrity in CIM by ensuring a high level of measurement accuracy. Through the use of less moving masses, more rigid constructions and faster probe systems, measuring time can be decreased to

allow a faster feedback of control data. Optical probe systems will be developed further and increasingly be employed on CMMs to allow faster measurements for their characteristic application areas. To overcome single probe system's specific disadvantages, multiprobe systems will be used on the same inspection task by using an automatic probe system changer. The different probe systems will be calibrated with respect to each other so that a high degree of accuracy can be guaranteed. As more and more CMMs will be used on the shop floor directly next to the production machines, guaranteeing a high accuracy level at the same time, it will become necessary to develop CMMs which are more resistant to a shop floor environment. Protection cabins around the CMM might be one solution but this complicates access to the machine. Employing new construction materials, optimizing the design and protecting the scales and guide ways better are other ways to improve shop floor application of the CMM. Off-line programming methods will be developed further and become more popular in use to decrease setup downtime of the machines. The development of expert systems, their integration in the CMM programming process will support untrained and inexperienced operators to program CMMs without operator influence to ensure accurate measuring results. Therefore to integrate the CMMs into CIM to share data with manufacturing, quality control and management, it is necessary to standardize data interfaces in the future. Aside from dimensional inspections, surface roughness and hardness tests will become possible on the CMMs which will make the CMMs of the future into a multi-purpose inspection device.

APPENDIX A

Environmental Guideline

This Appendix shows in form of a table the environmental guideline from the CMM-manufacturer Leitz Messtechnik GmbH, Germany for the CMM model PMM 181210 [4].

Operational Temperature Range	15 — 30°C
Reference Temperature	20°C (67°F)
Relative Humidity	40 — 60 %

Temperatures of the measuring room to ensure the specified measurement accuracy:

The base temperature is the reference temperature. By use of temperature correction, an arbitrary base temperature in between the operational temperature range is permissible. Varies the ground temperature by more than 0.5°C of the base temperature a thermal isolation has to be installed.

	standard Performance	enhanced Performance
Horizontal Temperature Gradient	< 0.7 K / 1.0 m	< 0.7 K / 1.0 m
Vertical Temperature Gradient	< 0.75 K / 1.0 m	< 0.75 K / 1.0 m < 1.0 K / 2.0 m
Time Range Hour:	$\Delta T/\Delta t \leq 1.0 \text{ K/ h}$	$\Delta T/\Delta t \leq 0.5 \text{ K/ h}$
Time Range Day:	$\Delta T/\Delta t \leq 0.5 \text{ K/ d}$	$\Delta T/\Delta t \leq 0.5 \text{ K/ h}$
Base Temperature Range:	16 — 25 °C	18 — 22 °C

Permissible vibrations of the supporting surface:

Maximum by use of a passive shock-absorbing isolation	f < 10 Hz	Amplitude 0.3 μm
	10 Hz < f < 30 Hz	Amplitude 0.05μm
	30 Hz < f	Amplitude 1.0 μm
Maximum by use of a pneumatic shock-absorbing isolation	f < 10 Hz	Amplitude 10 μm
	f > 10 Hz	Amplitude 20 μm

Table A1 An Example of Environmental Guidelines for a CMM [4]

APPENDIX B

Performance Test Protocols

This appendix shows in form of figures simplified measurement protocols for an example test report according to the VDI/VDE-Richtlinie 2617 [59].

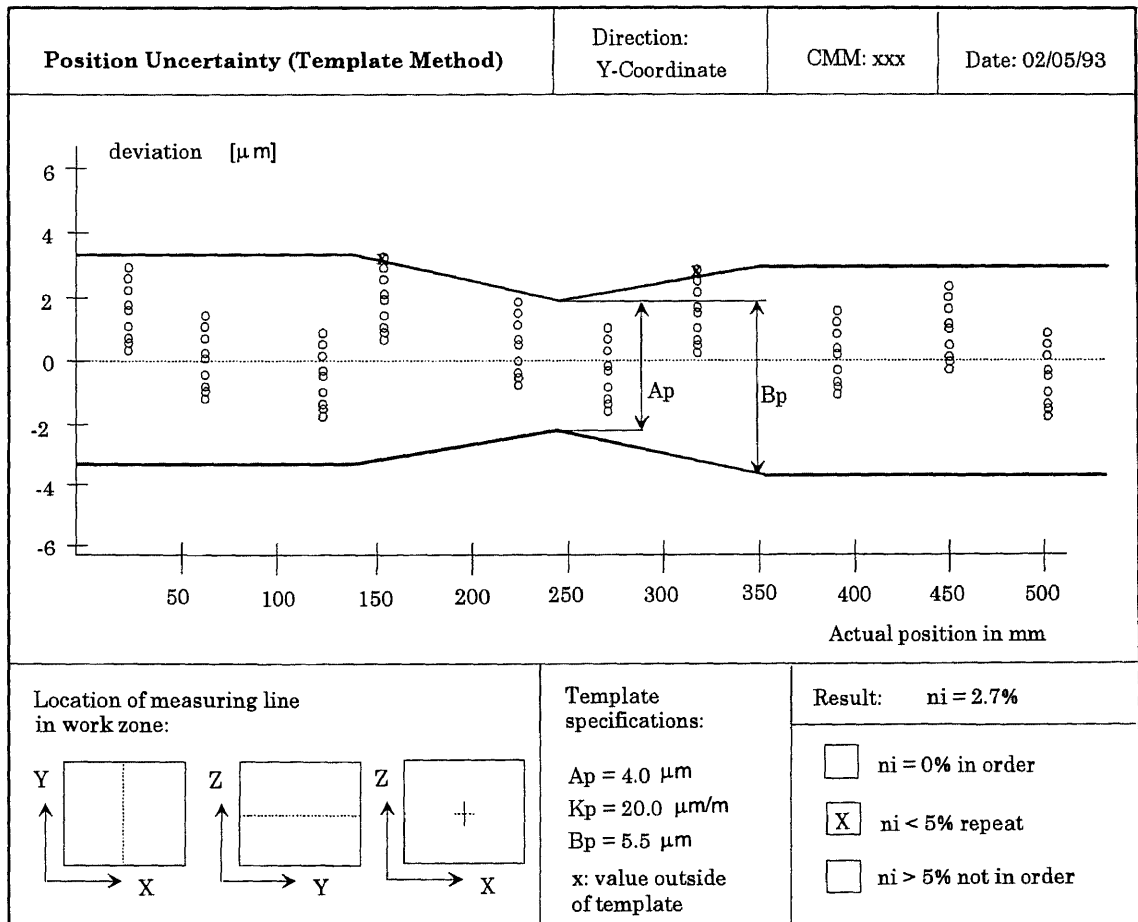


Figure B1 Measurement Protocol for Position Uncertainty using the Template Method

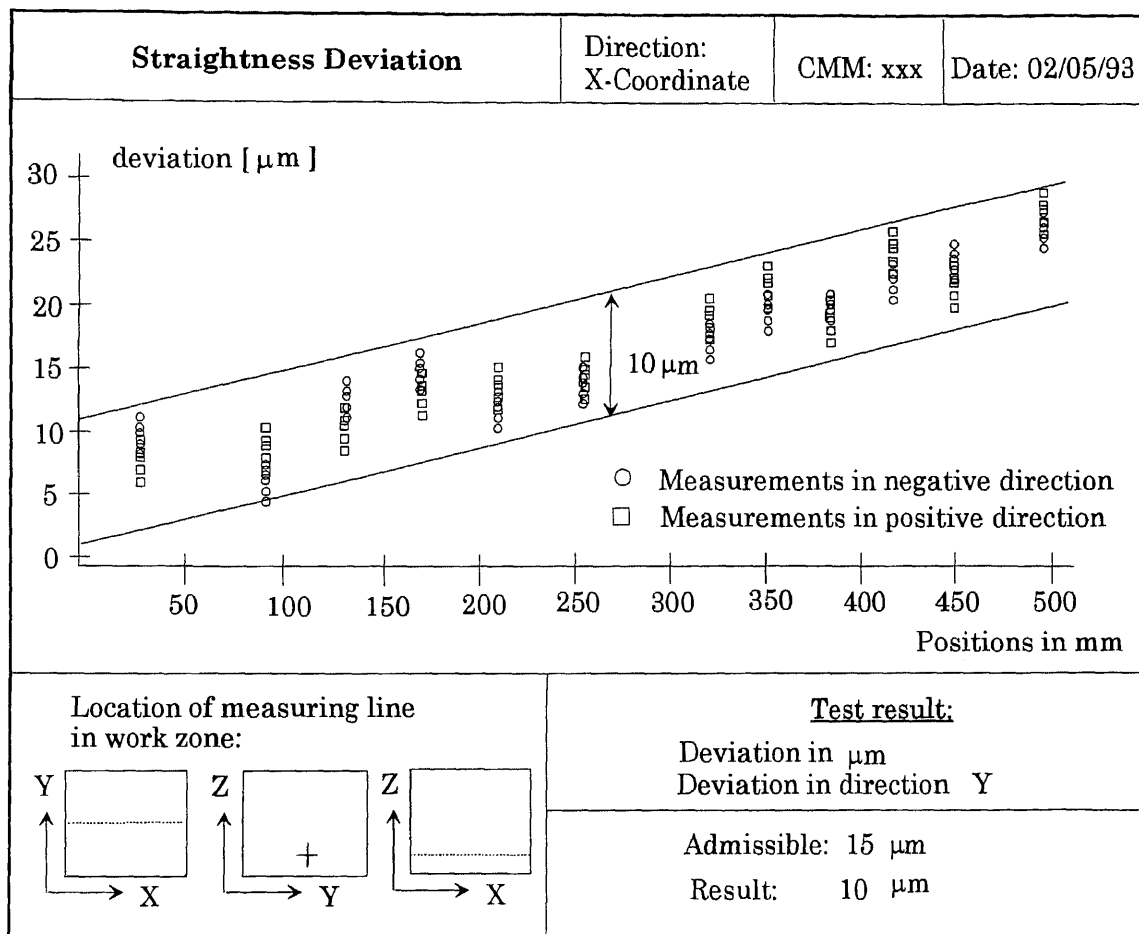


Figure B2 Measurement Protocol for the Straightness of a Coordinate Axis

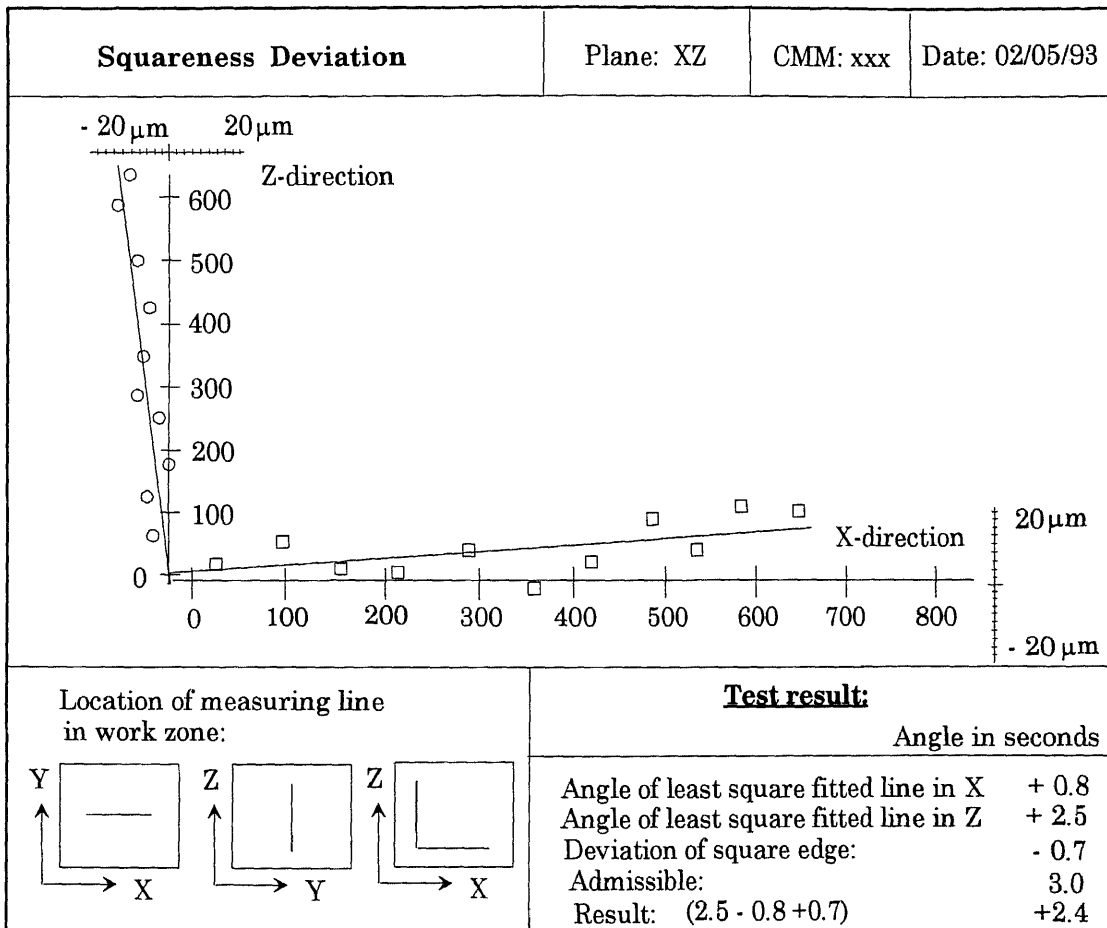


Figure B3 Measurement Protocol for the Squareness of two Coordinate Axes

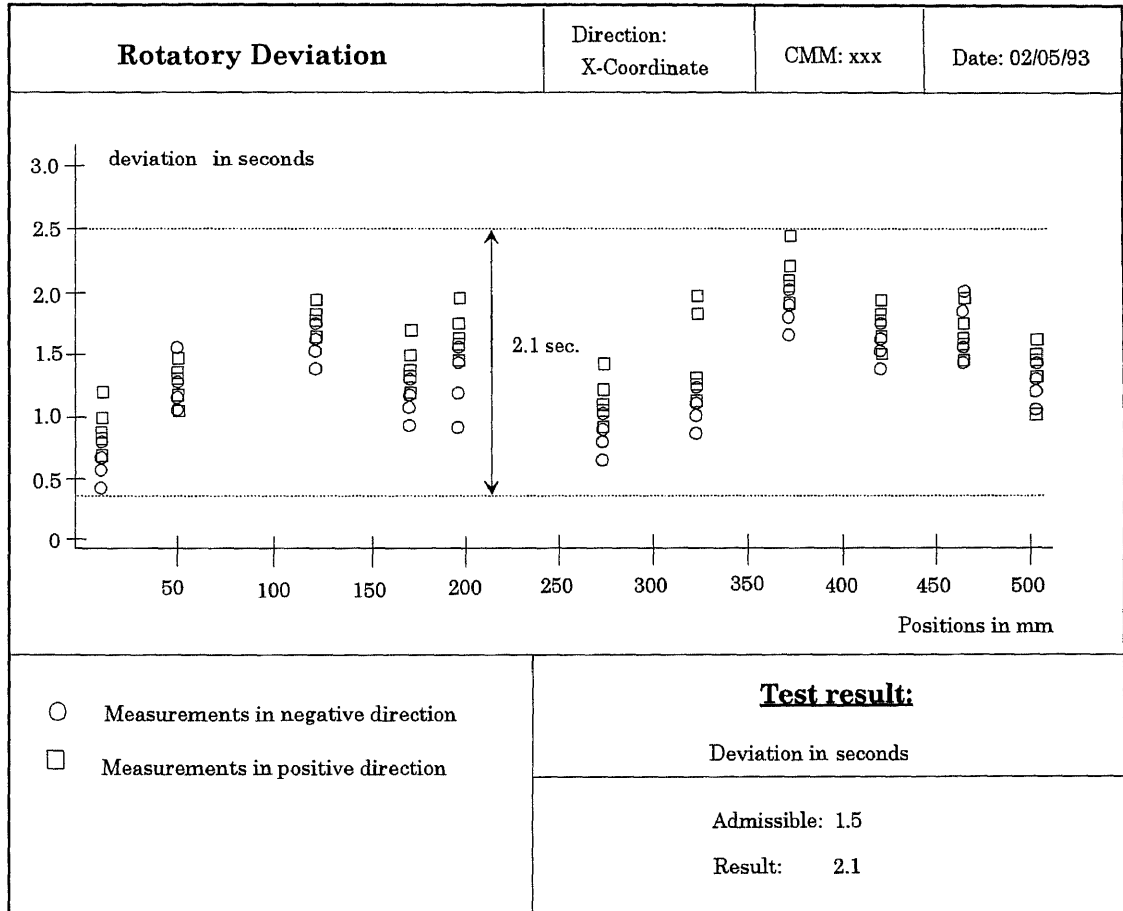


Figure B4 Measurement Protocol for the Rotatory Movement along an Axis of Travel

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