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THE ROLE OF COORDINATE MEASURING MACHINES (CMM) IN CAM

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1.0 The Principle of Multi-Coordinate Metrology

In recent years, especially over the last decade or so, multi-coordinate metrology has experienced a rapid development. Only ten years ago production plants and metrology labs were kept strictly separate and the Quality Inspection function kept more or less isolated from the production environment.

1.1 Conventional Metrology

The standard equipment in the metrology laboratory was length measuring comparators for gauge inspection, measuring microscopes for the two-dimensional checking of small parts, angle measuring devices and dividing heads. Larger parts were measured in one dimension on surface measuring plates with vertical micrometers and dial gauge support stands. With the help of angle plates it was possible to determine two-dimensional measure such as centre distances.

In the case of more complex inspection applications, jig boring machines were converted to measuring machines whose perpendicular guideways formed a 3-D cartesian reference system. The major problem was alignment of test piece with respect to the machine axes; a great number of auxiliaries, such as adjusting devices, setting plugs and angle plates were required. The scale displays were read off, recorded manually, and processed into measuring results to be appropriately documented.

1.2 Computer-aided Metrology

The first step towards a reduction of subjective influences and an increase in the measuring rate was the installation of digital measuring systems in conventional measuring equipment. Using electronic data collection equipment it was possible to read the data directly into a computer and process, producing an output of the desired form such as graphics and form plots.

Thus Computer-Aided Inspection (CAI) was established. Further development of metrological instruments concentrated largely on the 3-D Cartesian reference coordinate system. The development of Universal Measuring Machine (UMM), now perhaps better known as *Coordinate Measuring Machine (CMM)*, was the forerunner of a new era of metrology. It was based on the realisation that all the different geometric workpiece dimensions and forms could only be measured satisfactorily with a 3-D measuring system, where the different tips of a *probe arrangement* act as one common mathematical point which probes any testpiece surface within the coordinate system. The test piece position with respect to the reference coordinate system defines the spatial coordinates of the surface point. From several points determined in this way the geometric elements making up the surface can be computed.

2.0 Measuring Concepts and Coordinate Systems

The machine guideways form a Cartesian reference coordinate system X_m, Y_m, Z_m (*Machine Coordiante System - MCS*) with respect to which the probe head moves (Fig.1). The travel paths are measured by means of digital measuring systems of high resolution and precision. For the probe head, a spatial reference point of no dimension is defined. This may be, for example, the centre point of a probing element (probe tip or stylus).

(Here, it is appropriate to make a distinction between the items *probe head* and *probing element* [see Figure 2]. A probe head may carry several probing elements of different sizes and types as demanded by the particular measuring problem and to gain access to any workpiece point.)

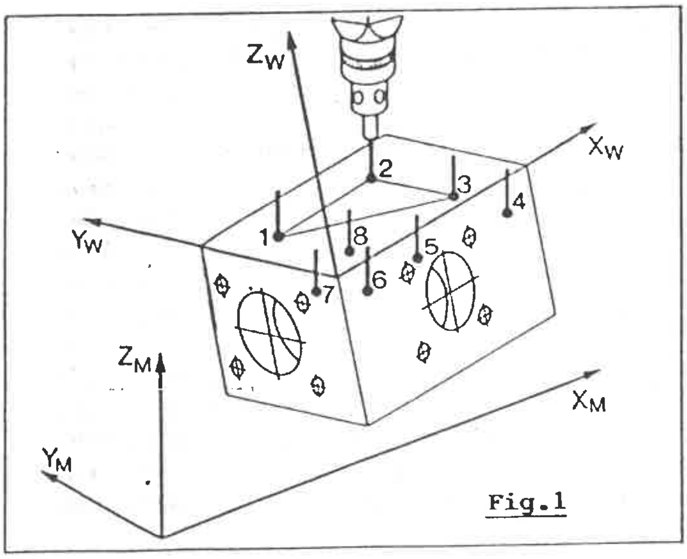

Fig.1

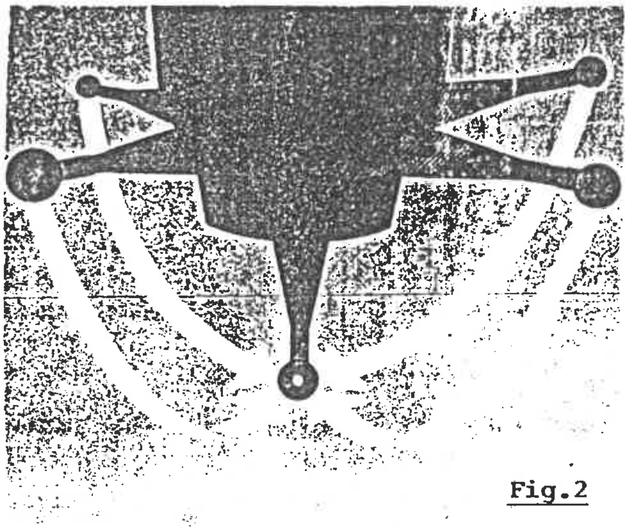
Fig.2

In Fig.1, the *Workpiece Coordinate System (WCS)* is designated by X_w, Y_w, Z_w. As the testpiece can be placed in any position on the machine table, the two coordinate systems do not normally coincide. The exact position of the WCS is defined by probing a number of surface points as required. In the example illustrated in Fig.1, the surface normal (direction of Z_w) is measured with points 1,2,3; with points 4,5 direction X_w is measured and with points 6,7,8 the origin is fixed. Once the WCS is established the test piece is *mathematically aligned* and the MCS can be mathematically referred to the WCS. Thus mechanical alignment of the test piece, one of the main requirements of conventional metrology, is completely dispensed with.

As mentioned earlier the different probe tips of the probing head must be identified as a single mathematical point. The coordinate differences between the reference point (ie. origin of the MCS) and the centre points of individual probe tips are compensated by a calibration measurement of all probing elements on a calibration sphere (*Master Ball*). This procedure also recognises and compensates for individual probe tip diameters. After the calibration process, the different probe tip diameters and centre point coordinates are automatically accounted for by the software and reduced to a point of zero dimension (see Figure 2).

Thus a CMM can check feature location, distances between features and shape/form definition without repositioning the part. What a CMM can accomplish might otherwise require a multiplicity of machines, instruments and a surface plate.

3.0 CMM Hardware

Most CMMs are of robust gantry-type construction, but for extended measuring ranges cantilever-type machines are also in use. Double-column cantilever-type machines with two probing units which can jointly measure large testpieces such as sheet metal parts in automobile and aircraft industries can perhaps be regarded as the most advanced versions. For base plate and guideway element construction, steel has been replaced by granite which has high dimensional stability and bending resistance. The guideways of the X,Y,Z axes are precision-lapped and sliding members move on air bearings which ensure friction and wear free smooth operation. The travel paths are measured by means of digital measuring systems of high resolution and precision. Probe displacement is detected and signalled by optical glass scale type linear encorders attached to the X,Y and Z axes and instantaneous position of the machine is thus registered by the computer when triggered by the probe head.

Both manual and CNC Control types are available. The latter requires further machine elements such as motor drives and recirculating ball bearings, and the CNC control unit itself.

The measuring uncertainties range from 0.0005mm (for precision CMMs) to 0.5mm.

3.1 Rotary Indexing Table

In many cases the use of a rotary indexing table slimplifies and speeds up the measurement of parts symmetrical about an axis such as gears. In CNC operation, a computer-controlled indexing table can be utilised as a *fourth measuring axis*. For example, fully automatic measurement of cam shafts is made possible by employing the fourth axis.

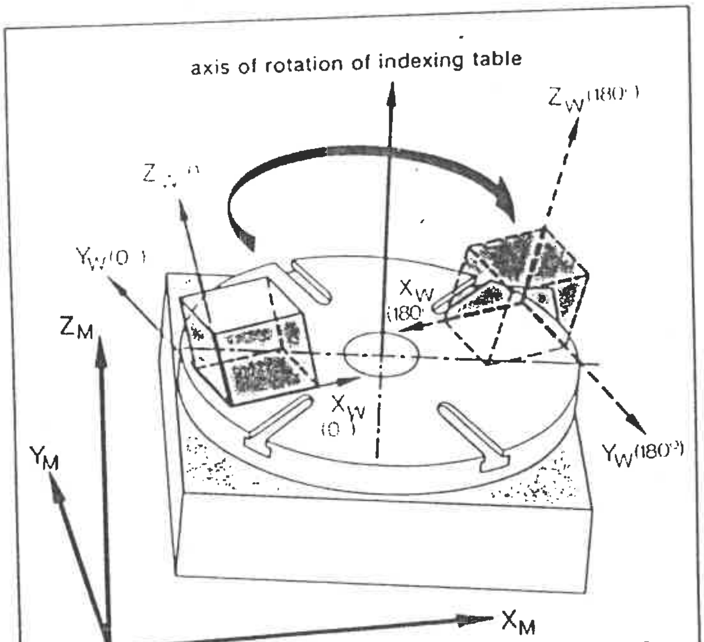

Fig.3

Fig.3 illustrates a testpiece mounted on a rotary indexing table. *The testpiece need not be centred with respect to the indexing table axis*. The eccentricity and skewness between the testpiece and the table axes can be initially determined and automatically compensated in later measurements. WCS is defined in 0° and 180° positions of the table; the symmetric line of the two Z-axes measured is the axis of the indexing table. After this initial calibration process, the measuring programme takes note of WCS in table rotation, saving time and auxiliaries required for centering of the testpiece.

3.2 Probe Head

The integrity of the probe head is most vital to accuracy in measurement. There are basically two types of probe heads used in CMMs.

a) Universal 3-D probe head ('Inductive type') and
b) Trigger probe head ('Switch type')

The *3-D Probe head* is a sophisticated device based on an inductive linear measuring system and is regarded as a miniature three-coordinate measuring machine in itself. With this type, it is possible to travel transverse to probing direction with the probe maintaining contact with the testpiece. Thus it can be used for surface scanning with continuous data transfer. The scanning mode is particularly useful in profile measurements where a great many measuring points are required to assess the geometry. The 3-D probe head is exclusively for use on CNC CMMs.

In the *Trigger probe head*, which is much simpler, the probing elements are connected to the housing through a spring-back mechanism. This mechanism protects the probing elements against damage when contact is made. An electronic sensor records probing element contacts with the testpiece even at measuring forces well below 0.01N. The data transfer to the computer takes place at the moment of contact. The trigger probe head can be used on manual CMMs as well as on CNC versions. It is widely used on shop floor inspection type CMMs.

4.0 CMM Software

A major factor in satisfactory implementation of advanced measurement technolgies is the quality of software. For CMMs, special software facilitates every measuring task from single to multi-dimensional on varied geometries. Moreover, CMM software capabilities generally cover data evaluation and documentation requirements as well. Menu-driven user interface, which requires minimum programming skills on the part of the operator, is a standard feature in all commercial software.

4.1 Standard Measurement Software

The basic software modules contain the routines for the measurement, storage and compensation of the centre point coordinates and diameters of probing elements, and for the transformation of probing points from the MCS into the WCS. In addition to this, routines defining indexing table axis rotation within the MCS, routines determining the eccentricity and offset centre errors between the main workpiece axis and the indexing table axis and routines converting all measurement points into the WCS are also available.

Standard software comprises 'definition programs' for the basic elements, POINT, STRAIGHT LINE, PLANE, CIRCLE, ELLIPSE, CYLINDER, CONE and SPHERE, 'Combination programs' such as distance, symmetry, section and perpendicularity, 'conversion programs' such as division, polar coordinates and angle and 'evaluation programs' for dimensional and positional tolerances.

4.2 Surface Scanning Programs

Apart from the above mentioned regular boundary surfaces (viz. plane, cylindrical, conical and spherical), routines are available for irregularly curved surfaces:

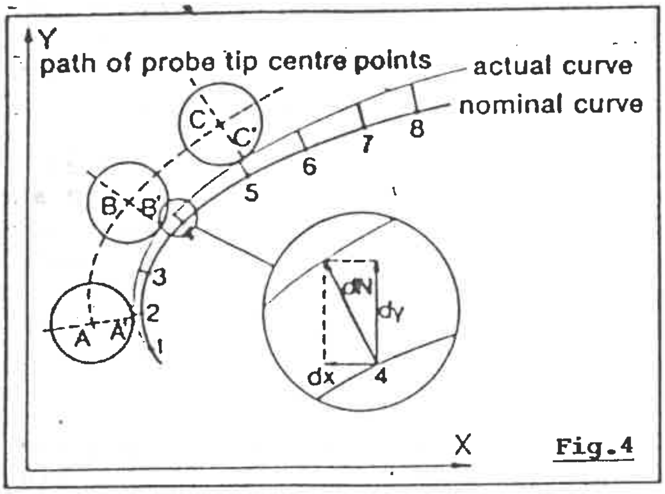

Fig.4

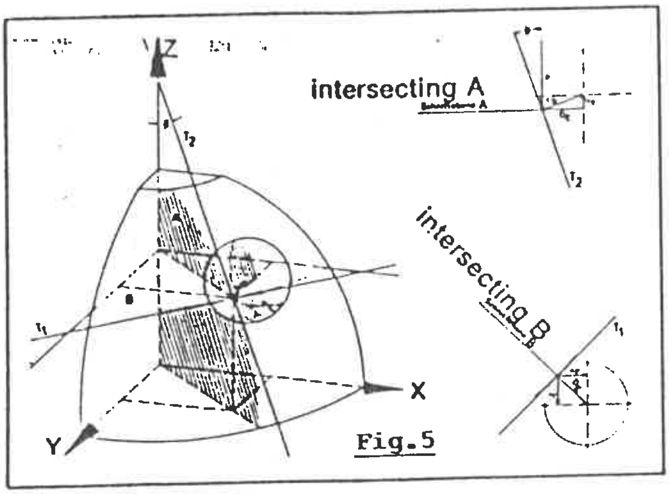

Fig.5

Surfaces curved in One direction - such as cams. Fig.4 illustrates the procedure for the determination of surface points on a surface curved in one direction derived from the probe tip centre point coordinates. From at least three neighbouring centre points a curve path is calculated. After computation of the normal direction, the profile surface points are obtained through vectorial addition of the probe tip radius.

Surfaces curved in Two directions - such as flanks of spiral bevel gears, car bodies. The surface points of surfaces curved in two directions are determined in a similar way. The normal of a small surface element, and thus the spatial vector for the probe tip radius is determined from at least three probing points which are located near the measuring pont but not in one section.

Surfaces curved in Three directions - Fig. 5 illustrates the geometric relationships on a surface curved in three dimensions. If the curves are defined through mathematical functions, or the surface points and the normal vectors are known the measuring and evaluation processes are simplified. However, the same principle can be applied to any unknown contour.

Special software packages are available for special applications such as compound curved surface digitisation and measurement (for example in impeller measurement), gear and cam inspection and for statistical analysis.

4.3 Machine Control Software

The computer system of CNC CMMs is fully integrated with the machine controller and works in conjunction with powerful software. These systems recognise probing directions automatically, determine probe diameter corrections, selects operating planes and distinguishes internal from external diameters automatically. CNC operation is supported by self-teaching programming systems and editors, permitting programmes to be written by simply measuring the part.

To illustrate some of the software concepts and features discussed in the preceeding paragraphs, the reader is referred to some commercial software details presented as an Appendix to this paper. {Reference: *Mitutoyo CMM Catalogue,* Courtesy: *Mitutoyo Asia Pacific}*

5.0 **Role of CMM in CAM**

From the foregoing presentation of CMM Hardware facilities and Software capabilities, it becomes clear that considerable scope and flexibility exists for incorporating these machines in a Computer Integrated Manufacturing (CIM) environment.

In-process Inspection has taken on great significance in recent years. High accuracy, automatic probe changers and the ability to function in machine shop environments have led to frequent incorporation of CNC CMM's in Flexible Manufacturing Systems(FMS). A CMM is in effect a cartesian robot: the three axes of motions are orthogonal translations and the probe arrangement acts as the 'wrist' allowing for roll, pitch and yaw motions required for accurate measurement sensing. The CMM can be programmed to inspect parts automatically according to a pre-defined measuring path.

Fig.6 illustrates the features of a typical CIM system. The *Dimensional Measuring Interface Specification (DMIS)* was developed to provide an interfacing standard for bidirectional communication of inspection data between CAD systems and computerised inspection equipment. DMIS defines a high-level language with an APT-like vocabulary that establishes a neutral or generic format for exchanging inspection programs and inspection data between automated equipment such as CAD systems, CMMs and quality information systems. This standard is an important development in achieving a CIM environment. Part-programs for measurement are prepared away from the CMM even before the part has been fabricated. Later learn programming on the CMM can be used to correct part programs prepared away from the machine and to insert data in complex places during a test run.

THE MITUTOYO PATH TO COMPUTER INTEGRATED MANUFACTURING

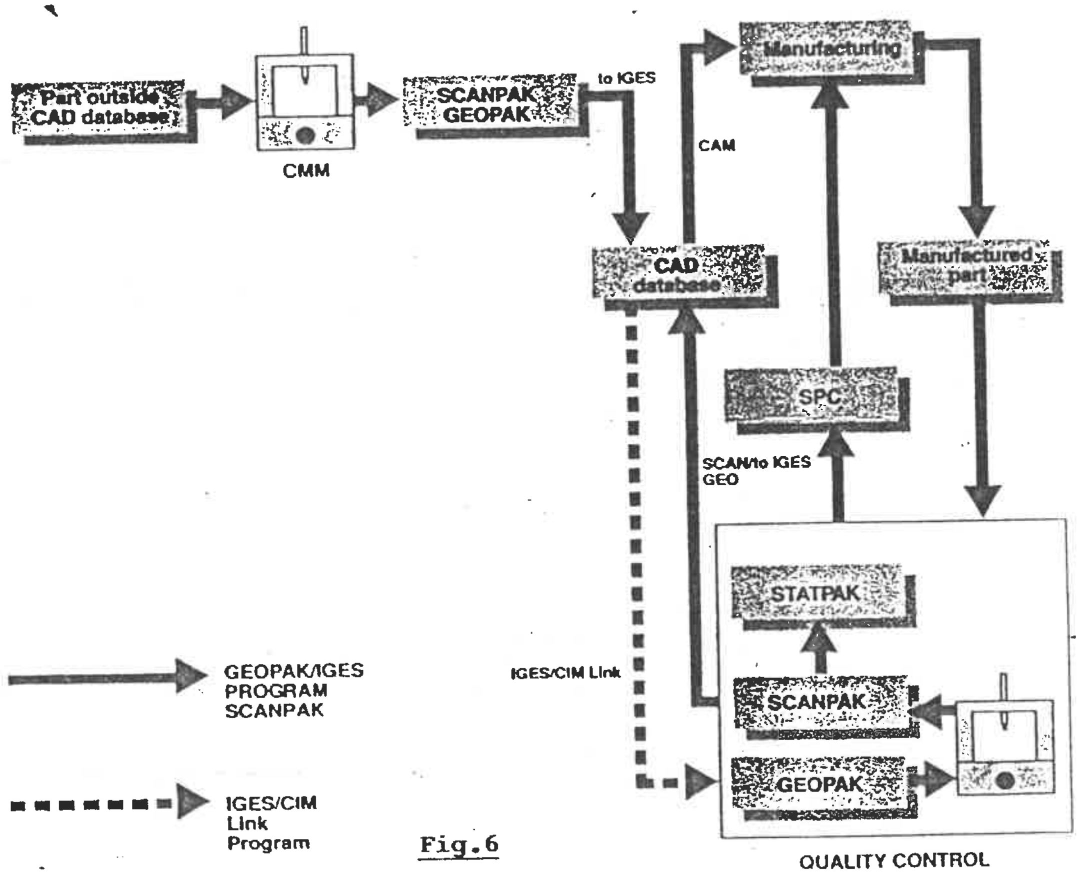

Fig.6

An entirely different but most useful application is in the 'reverse engineering problem' where a previously manufactured complex part has to be reproduced in exact detail or in a modified form with no production drawings or design specifications being available to the machinist. Here, all the dimensions have to be extracted from the given part. The data generated by surface scanning can be transferred to a CAD program. The points measured are joined to create a polygon and can then be manipulated using all the functions available in the CAD program.

Apart from the FMS applications, A CMM is especially effective for the first article inspection of small-batch complex parts that are made on CNC machines. Under these conditions, the manufacturing costs are high and it is uneconomical to provide in process gauging.