MODULE 4

MACHINE TOOL METROLOGY

Machine tool metrology is primarily concerned with the geometric tests of the alignment accuracy of machine tools under static conditions. It is important to assess the alignment of various machine parts in relation to one another. It is also necessary to assess the quality and accuracy of the control devices and the driving mechanism in the machine tool. In addition to geometric tests, practical running tests are also performed to assess the accuracy of a machine tool.

The typical geometric tests conducted for machine tools comprise tests for straightness, flatness, squareness, and parallelism. Running tests are conducted to evaluate geometric tolerances such as roundness and cylindricity.

ALIGNMENT TESTS ON LATHE

The following are the important tests carried out on a lathe:

Levelling of machine: The machine should be installed such that the lathe bed is truly horizontal. A sensitive spirit level or a clinometer can be used to verify the levelling of the machine. The spirit level is moved over the designated distance specified in the test chart, and the deviation is noted down. The test is carried out in both longitudinal and transverse directions. The positioning of the spirit level on a guideway is illustrated in Fig.

True running of main spindle: The main spindle, while running, should not have any play or radial deviations from its axis. This is tested using a test mandrel of acceptable quality. The mandrel is fitted to the spindle bore and the dial indicator feeler is made to contact the mandrel surface as shown in Fig. The spindle is gently rotated by hand, and the deviations of the dial indicator are noted down. The dial indicator base is mounted on the carriage. The deviation should be within acceptable limits.

Axial slip of main spindle: The spindle should have true running in a direction parallel to its axis. This is checked by placing the dial indicator feeler against the spindle face and giving slight rotation to the spindle. The deviations should be within acceptable limits. The test is repeated at a diametrically opposite location to ensure that the spindle does not have an axial slip.

Levelling of the machine   True running of the main spindle   Axial slip of the main spindle
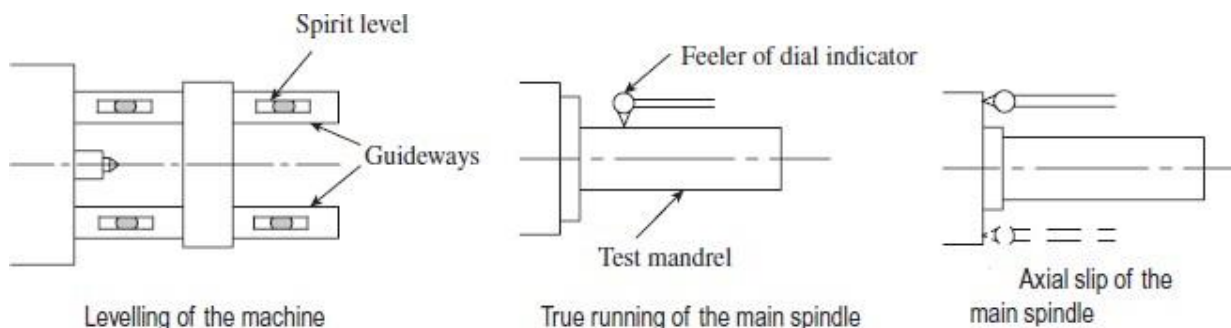
True running of headstock centre: The headstock centre is the live centre of the machine; if it is not true, accuracy of the workpiece will suffer. The workpiece will develop eccentricity if the error is too much. The feeler of the dial indicator is pressed perpendicular to the taper surface of the centre, and the spindle is rotated. The deviation indicates the trueness of the headstock centre.

Parallelism of main spindle: Parallelism of the spindle is crucial for generating accurate dimensions. Any error in parallelism will result in a tapered surface after machining. In order to test parallelism, a test mandrel is made use of. It is fitted into the spindle bore and dial gauge readings are taken over a specified length, as. Two readings are taken, one in a horizontal plane and the other in a vertical plane, on one of the sides of the mandrel. It is important to see that excess overhang of the mandrel does not result in a sag due to its own weight.

True running of taper bore of main spindle: The lathe spindle bore has a standard taper. Unless this taper is concentric with the spindle axis, workpieces will have undesired taper or eccentricity. A test mandrel is fitted to the tapered bore of the spindle, and dial gauge readings are taken at the two extreme ends of the mandrel. This value should be well within the allowable limits.

True running of the headstock centre

Parallelism of main spindle

True running of a spindle taper bore
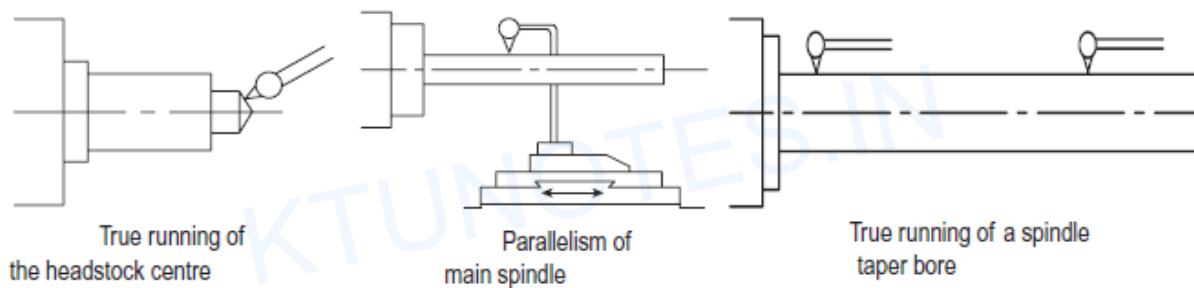
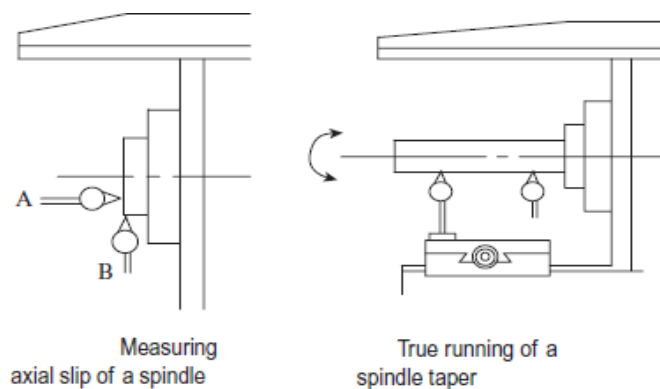ALIGNMENT TESTS ON MILLING MACHINE

Axial slip of spindle: A spindle may have an axial slip, which is the axial movement of the spindle during its rotation. Axial slip may occur due to the following reasons: errors due to worn-out spindle bearings, face of the locating shoulder of the spindle not being in a plane perpendicular to the axis of the spindle, and irregularities in the front face of the spindle.

The feeler of the dial gauge is held against the front face of the spindle and the base is mounted on the table. The position of the dial gauge (in order to measure axial slip) is denoted by A in the figure. The spindle is gently rotated by hand and the dial gauge reading is noted down. The test is repeated at a diametrically opposite spot. The maximum deflection should be well within the prescribed limits.

Eccentricity of external diameter of spindle: Position B of the dial gauge shown in the left side Fig. is used to determine the eccentricity of the external diameter of the spindle. The feeler is made to contact the spindle face radially, and the dial gauge base is mounted on the machine table. The spindle is gently rotated by hand and the dial gauge deviation is noted down. The maximum

deviation gives the eccentricity of the external diameter of the spindle, and it should be well within specified limits.

True running of inner taper of spindle: The spindle of a milling machine is provided with a standard taper, which matches with the tooling used on the machine. The axis of the taper should be perfectly coincident with the axis of the spindle. Otherwise, the workpieces will develop undesired taper or eccentricity after machining. This condition is checked by using a test mandrel that fits into the spindle taper. The dial gauge is mounted on the machine table, and the feeler is made to contact the mandrel at one end of the mandrel, as shown in Fig. Maximum deviation of the dial gauge is noted by gently rotating the spindle by hand. The test is repeated at the other end of the mandrel.

Measuring
axial slip of a spindle

True running of a
spindle taper

ALIGNMENT TESTS ON DRILLING MACHINE

Squareness of spindle axis with table: In order to determine the error in squareness, the spindle is moved by 180°.

Total deflection of spindle: During the drilling operation, the spindle experiences high axial force. The spindle should not deflect excessively due to this force. Otherwise, the drilled hole will have error of straightness and eccentricity. In order to evaluate deflection of the spindle, a drill tool dynamometer (DTD) is used. The DTD provides a means of applying a known amount of load on the spindle.

The drill spindle is loaded by moving the drill head downwards and recording the value of force on the DTD display screen. The base of the dial indicator is placed on the machine table. The feeler is held against the spindle face. The recommended pressure is applied on the spindle and the dial gauge deflection is noted down.

True running of spindle taper: The true running of a spindle taper is tested using a test mandrel. The test Mandrel is loaded in the spindle and the dial gauge base is fixed on the machine table. The feeler is made to contact the mandrel surface and the spindle is gently rotated by hand. The dial indicator reading is noted down and it is ascertained if the reading is within permissible limits. The test is repeated at three different locations to ensure its validity.

Squareness of the spindle axis with table   Deflection of a spindle   True running of a spindle taper
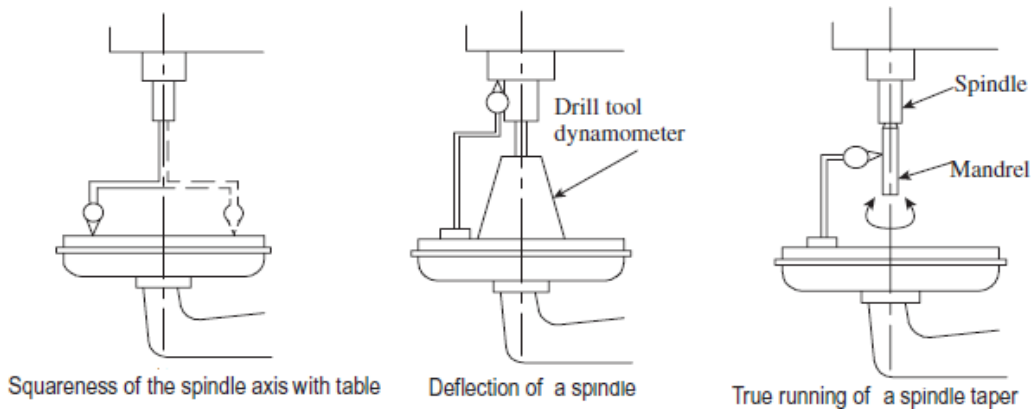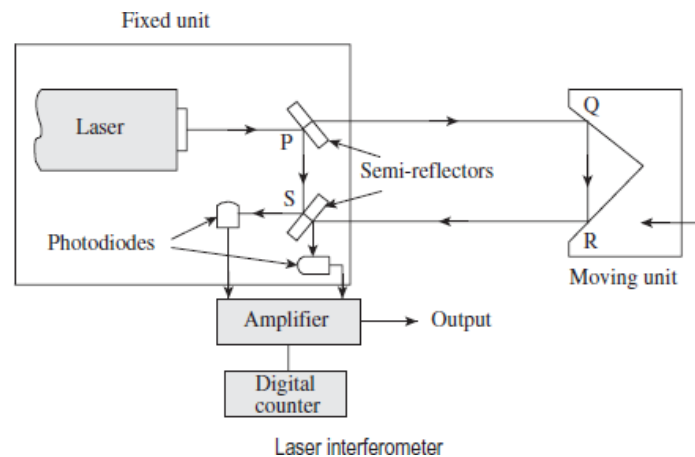
LASER INTERFEROMETERS

Lasers were more used by physicists than engineers, since the frequencies of lasers were not stable enough. However, stabilized lasers are used along with powerful electronic controls for various applications in metrology. Gas lasers, with a mixture of neon and helium, provide perfectly monochromatic red light. Interference fringes can be observed with a light intensity that is 1000 times more than any other monochromatic light source. Laser-based instruments are extremely costly and require many accessories, which obstruct their usage.

More importantly, from the point of view of calibration of slip gauges, one limitation of laser is that it generates only a single wavelength. This means that the method of exact fractions cannot be applied for measurement. In addition, a laser beam with a small diameter and high degree of collimation has a limited spread. Additional optical devices will be required to spread the beam to cover a larger area of the workpieces being measured.

From the measurement point of view, laser interferometry can be used for measurements of small diameters as well as large displacements. The fixed unit called the laser head consists of laser, a pair of semi-reflectors, and two photodiodes. The sliding unit has a corner cube mounted on it. The corner cube is a glass disk whose back surface has three polished faces that are mutually at right angles to each other. The corner cube will thus reflect light at an angle of 180°, regardless of the angle at which light is incident on it. The photodiodes will electronically measure the fringe intensity and provide an accurate means for measuring displacement.

Laser light first falls on the semi-reflector P, is partially reflected by 90° and falls on the other reflector S. A portion of light passes through P and strikes the corner cube. Light is turned through 180° by the corner cube and recombines at the semi-reflector S. If the difference between these two paths of light (PQRS − PS) is an odd number of half wavelengths, then interference will occur at S and the diode output will be at a minimum. On the other hand, if the path difference is an even number of half wavelengths, then the photodiodes will register maximum output. Each time the moving slide is displaced by a quarter wavelength, the path difference (i.e., PQRS − PS) becomes half a wavelength and the output from the photodiode also changes from maximum to minimum or vice versa. This sinusoidal output from the photodiode is amplified and fed to a high-speed counter,

which is calibrated to give the displacement in terms of millimeters. The purpose of using a second photodiode is to sense the direction of movement of the slide.

Laser interferometer

Laser interferometers are used to calibrate machine tables, slides, and axis movements of coordinate measuring machines. The equipment is portable and provides a very high degree of accuracy and precision.

COORDINATE MEASURING MACHINES (CMM)

Coordinate measuring machine refers to the instrument/machine that is capable of measuring in all three orthogonal axes. A CMM enables the location of point coordinates in a three-dimensional (3D) space. It simultaneously captures both dimensions and orthogonal relationships. CMM is integrated with a computer which provides additional power to generate 3D objects as well as to carry out complex mathematical calculations. Complex objects can be dimensionally evaluated with precision and speed.

CMM can be used in situations that require:

Multiple features The more the number of features (both dimensional and geometric) that areto be controlled, the greater the value of CMM.

Flexibility It offers flexibility in measurement, without the necessity to use accessories such as jigs and fixtures.

Automated inspection Whenever inspection needs to be carried out in a fully automated environment, CMM can meet the requirements quite easily.
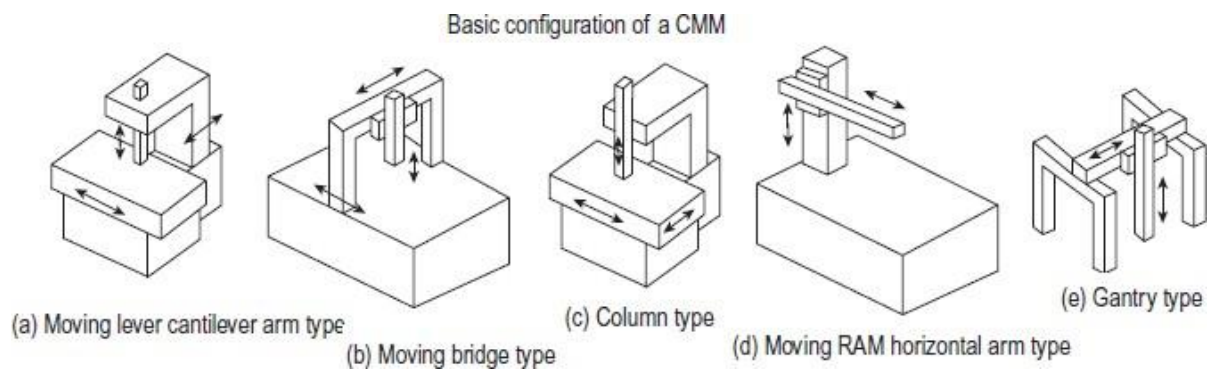
High unit cost If rework or scrapping is costly, the reduced risk resulting from the use of a CMM becomes a significant factor.

Structure

The basic version of a CMM has three axes, along three mutually perpendicular directions. Thus, the work volume is cubical. A carriage is provided for each axis, which is driven by a separate motor. While the straight line motion of the second axis is guided by the first axis, the third axis in turn is guided by the second axis. Each axis is fitted with a precision measuring system, which continuously records the displacement of the carriage from a fixed reference.

The third axis carries a probe. When the probe makes contact with the workpiece, the computer captures the displacement of all the three axes.

Depending on the geometry of the workpiece being measured, the user can choose any one among the five popular physical configurations. Figure below illustrates the five basic configuration types: cantilever, bridge, column, horizontal arm, and gantry.

Basic configuration of a CMM

(a) Moving lever cantilever arm type
(b) Moving bridge type
(c) Column type
(d) Moving RAM horizontal arm type
(e) Gantry type

Cantilever The vertically positioned probe is carried by a cantilevered arm. The probe moves up and down along the Z-axis, whereas the cantilever arm moves in and out along the Y-axis (lateral movement). The longitudinal movement is provided by the X-axis, which is basically the work table. This configuration provides easy access to the workpiece and a relatively large work volume for a small floor space.

Bridge A bridge-type configuration is a good choice if better rigidity in the structure is required. The probe unit is mounted on a horizontal moving bridge, whose supports rest on the machine table.

Column This configuration provides exceptional rigidity and accuracy. It is quite similar in construction to a jig boring machine. Machines with such a configuration are often referred to as universal measuring machines.

Horizontal arm In this type of configuration, the probe is carried by the horizontal axis. The probe assembly can also move up and down along a vertical axis. It can be used for gauging larger workpieces since it has a large work volume. It is often referred to as a layout.

Gantry In this configuration, the support of the workpiece is independent of the X- and Y-axis. Both these axes are overhead and supported by four vertical columns from the floor. The operator can walk along with the probe, which is desirable for large workpieces.

MODES OF OPERATION

CMMs can be classified into the following three types based on their modes of operation:

1. Manual

2. Semi-automated

3. Computer controlled

The manual CMM has a free-floating probe that the operator moves along the machine's three axes to establish contact with part features. The differences in the contact positions are the measurements.

A semi-automatic machine is provided with an electronic digital display for measurement. Many functions such as setting the datum, change of sign, and conversion of dimensions from one unit to another are done electronically.

A computer-controlled CMM has an on-board computer, which increases versatility, convenience, and reliability. Such machines are quite similar to CNC machines in their control and operation. Computer assistance is utilized for three major functions. Firstly, programming software directs the probe to the data collection points. Secondly, measurement commands enable comparison of the distance traversed to the standard built into the machine for that axis. Thirdly, computational capability enables processing of the data and generation of the required results.

PROBE

The probe is the main sensing element in a CMM. Generally, the probe is of 'contact' type, that is, it is in physical contact with the workpiece when the measurements are taken. Contact probes may be either 'hard' probes or 'soft' probes. However, some CMMs also use a non-contact-type. Figure illustrates the main components of a probe assembly. A probe assembly comprises the probe head, probe, and stylus. The probe is attached to the machine quill by means of the probe head and may carry one or more styli. Some of the probes are motorized and provide additional flexibility in recording coordinates.
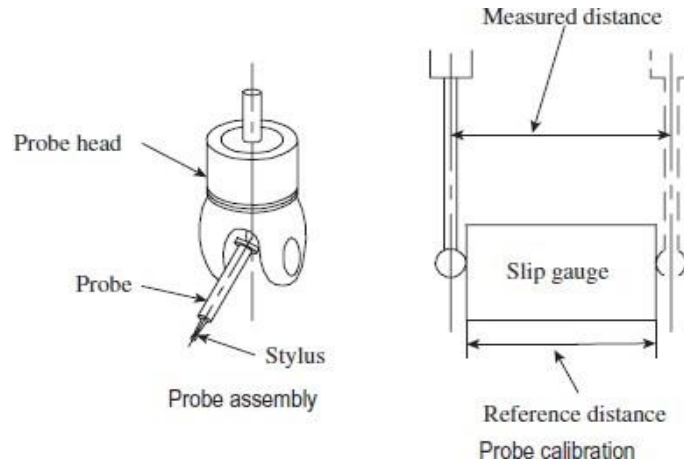
The stylus is integral with hard probes and comes in various shapes such as pointed, conical, and ball end. As a power feed is used to move the probe along different axes, care should be exercised when contact is made with the workpiece to ensure that excessive force is not applied on the probe. Excessive contact force may distort either the probe itself or the workpiece, resulting in inaccuracy in measurement. Use of soft probes reduces this problem to a large extent. Soft probes make use of electronic technology to ensure application of optimum contact pressure between the probe and the workpiece. Linear voltage differential transformer heads are generally used in electronic probes.

Some measurement situations, for example, the inspection of printed circuit boards, require non-contact-type probes. Measurement of highly delicate objects such as clay or wax models may also require this type of probe. Most non-contact probes employ a light beam stylus. This stylus is used in a manner similar to a soft probe. The distance from the point of measurement is known as standoff and is normally 50 mm. The system provides 200 readings per second for surfaces with good contrast. The system has high resolution of the order of 0.00005 mm. However, illumination of the workpiece is an important aspect that must be taken into consideration to ensure accurate measurement.

   PROBE CALIBRATION

A remarkable advantage of a CMM is its ability to achieve a high level of accuracy even with reversal in the direction of measurement. It does not have the usual problems such as backlash and hysteresis associated with measuring instruments. However, the probe may mainly pose a problem due to deflection. Therefore, it needs to be calibrated against a master standard. Figure 10.4 illustrates the use of a slip gauge for calibration of the probe.

Calibration is carried out by touching the probe on either side of the slip gauge surface. The nominal size of the slip gauge is subtracted from the measured value. The difference is the 'effective' probe diameter. It differs from the measured probe diameter because it contains the deflection and backlash encountered during measurement. These should nearly remain constant for subsequent measurements.

OPERATION

Most modern CMMs employ computer control. A computer offers a high degree of versatility, convenience, and reliability. A modern CMM is very similar in operation to a computer numerical control (CNC) machine, because both control and measurement cycles are under the control of the computer. User-friendly software provides the required functional features. The software comprises the following three components:

1. Move commands, which direct the probe to the data collection points

2. Measurement commands, which result in the comparison of the distance traversed to the standard built into the machine for that axis

3. Formatting commands, which translate the data into the form desired for display or printout

MACHINE PROGRAMMING

Most measurement tasks can be carried out using readily available subroutines. The subroutines are designed based on the frequency with which certain measurement tasks reappear in practice. An operator only needs to find the subroutine in a menu displayed by the computer. The operator then inputs the data collection points, and using simple keyboard commands the desired results can be obtained. The subroutines are stored in the memory and can be recalled whenever the need arises. Figure 10.5 illustrates a few typical subroutines that are used in CMMs.

A circle can be defined by specifying three points lying on it. This is shown in Fig. 10.5(a). The program automatically calculates the centre point and the diameter of the best-fit circle. A cylinder is slightly more complex, requiring five points. The program determines the best-fit cylinder and calculates the diameter, a point on the axis, and a best-fit axis (Fig. 10.5b).

Situations concerning the relationship between planes are common. Very often, we come across planes that need to be perfectly parallel or perpendicular to each other. Figure 10.5(c) illustrates a situation where the perpendicularity between two planes is being inspected. Using a minimum of two points on each line, the program calculates the angle between the two lines. Perpendicularity is defined as the tangent of this angle. In order to assess the parallelism between two planes (Fig. 10.5d), the program calculates the angle between the two planes. Parallelism is defined as the tangent of this angle. In addition to subroutines, a CMM needs to offer a number of utilities to the user, especially mathematical operations. Most CMMs have a measurement function library. The following are some typical library programs:

1. Conversion from SI (or metric) to British system

2. Switching of coordinate systems, from Cartesian to polar and vice versa

3. Axis scaling

4. Datum selection and resetting

5. Nominal and tolerance entry

6. Bolt-circle centre and diameter

7. Statistical tools

Typical subroutines used in a CMM (a) Circle (b) Cylinder
(c) Perpendicularity between two planes (d) Parallelism between two planes
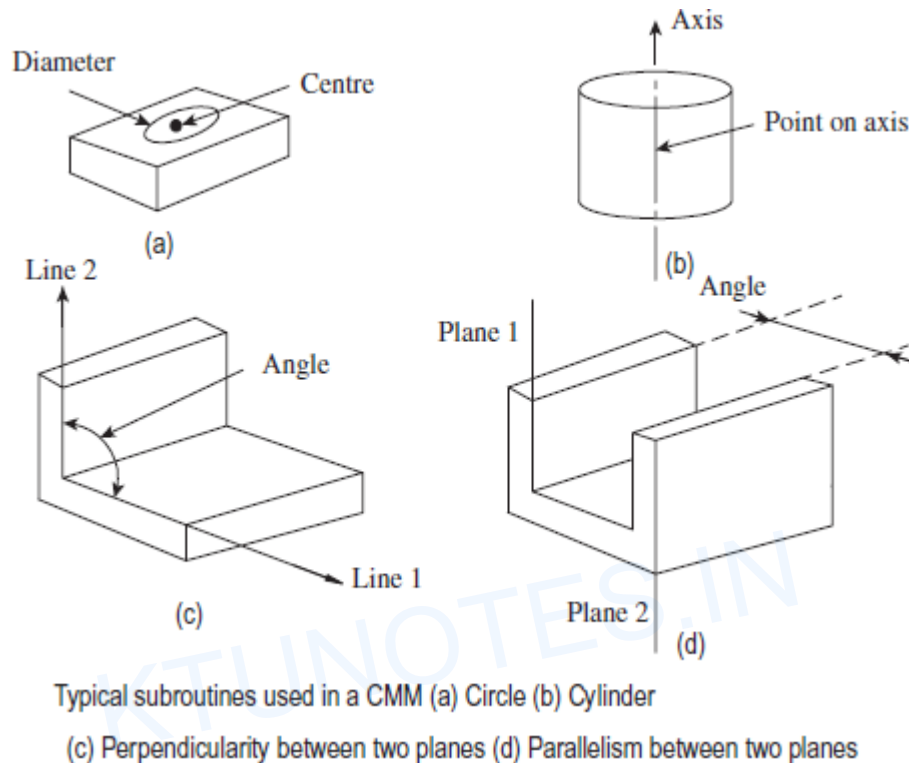
MAJOR APPLICATIONS

The CMM is sophisticated equipment, which offers tremendous versatility and flexibility in modern manufacturing applications. It uses the fundamental principles of metrology to an extent that is not matched by any other measurement instrument. However, its use is limited

to situations where production is done in small batches but products are of high value. It is especially useful for components of varied features and complex geometry. In addition to these factors, a CMM is a good choice in the following situations:

1. A CMM can easily be integrated into an automated inspection system. The computer controls easy integration in an automated environment such as an FMS or a CIM. The major economic benefit is the reduction in downtime for machining while waiting for inspection to be completed.

2. A CMM may be interfaced with a CNC machine so that machining is corrected as the work piece is inspected. A further extension of this principle may include computer-assisted design and drafting (CADD).

3. Another major use of CMMs is in reverse engineering. A complete 3D geometric model with all critical dimensions can be built where such models do not exist. Once the geometric model is built, it becomes easier to design dies or moulds for manufacturing operations. Quite often, companies create 3D models of existing critical dies or moulds of their competitors or foreign companies. Subsequently, they manufacture the dies, moulds, or components, which create a grey market for such items in the industry.
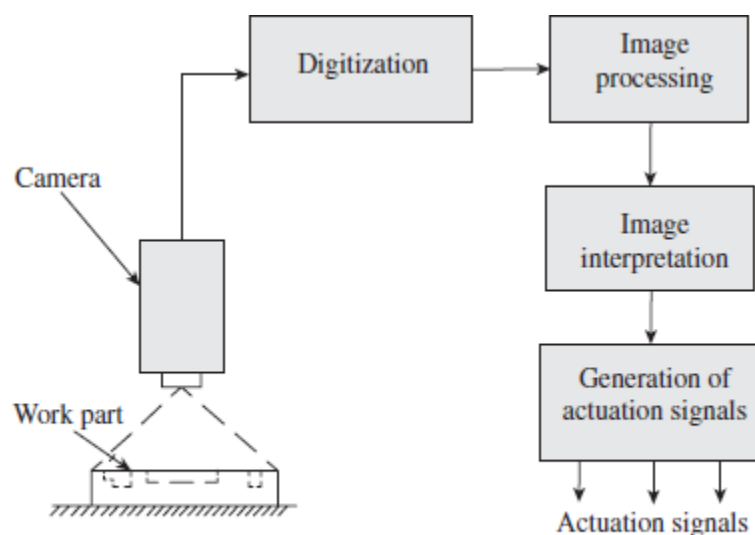
MACHINE VISION

Machine vision can be defined as the acquisition of image data of an object of interest, followed by processing and interpretation of data by a computer program, for useful applications. A machine vision system enables the identification and orientation of a work part within the field of vision, and has far-reaching applications. It can not only facilitate automated inspection, but also has wide ranging applications in robotic systems.

Stages of Machine Vision

The principal applications in inspection include dimensional gauging, measurement, and verification of the presence of components. The operation of a machine vision system involves the following four important stages:

1. Image generation and digitization

2. Image processing and analysis

3. Image interpretation

4. Generation of actuation signals

Configuration of a machine vision system

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Image Generation and Digitization

The primary task in a vision system is to capture a 2D or 3D image of the work part. A 2D image captures either the top view or a side elevation of the work part, which would be adequate to carry out simple inspection tasks. While the 2D image is captured using a single camera, the 3D image requires at least two cameras positioned at different locations. The work part is placed on a flat surface and illuminated by suitable lighting, which provides good contrast between the object and the background. The camera is focused on the work part and a sharp image is obtained. The image comprises a matrix of discrete picture elements popularly referred to as pixels. Each pixel has a value that is proportional to the light intensity of that portion of the scene. The intensity value for each pixel is converted to its equivalent digital value by an analog-to-digital converter (ADC).

This digitized frame of the image is referred to as the frame buffer. While Fig. (a) illustrates the object kept in the scene of vision against a background, Fig. (b) shows the division of the scene into a number of discrete spaces called pixels. The choice of camera and proper lighting of the scene are important to obtain a sharp image, having a good contrast with the background.

Vision system

(a)
Object and background

(b)
Matrix of pixels
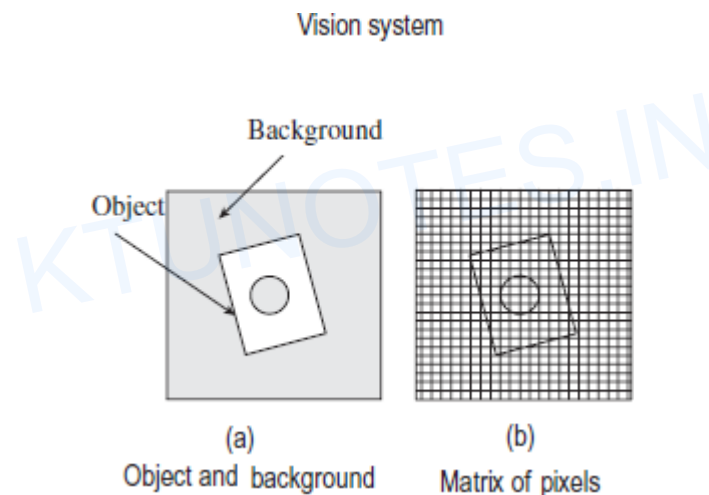
The image of the work part is focused onto a photoconductive surface, which is scanned at a frequency of 25–30 scans per second by an electron beam. The scanning is done in a systematic manner, covering the entire area of the screen in a single scan. Different locations on the photoconductive surface, called pixels have different voltage levels corresponding to the light intensity striking those areas. The electron beam reads the status of each pixel and stores it in the memory.

Solid-state cameras are more advanced and function in digital mode. The image is focused onto a matrix of equally spaced photosensitive elements called pixels. An electrical charge is generated in each element depending on the intensity of light striking the element. The charge is accumulated in a storage device. The status of every pixel, comprising either the grey scale or the colour code, is thus stored in the frame buffer. Solid-state cameras have become more popular because they adopt more

rugged and sophisticated technology and generate much sharper images. Charge-coupled-device (CCD) cameras have become the standard accessories in modern vision systems.

Image Processing and Analysis

The frame buffer stores the status of each and every pixel. A number of techniques are available to analyse the image data. However, the information available in the frame buffer needs to be refined and processed to facilitate further analysis. The most popular technique for image processing is called segmentation. Segmentation involves two stages: thresholding and edge detection.

Thresholding converts each pixel value into either of the two values, white or black, depending on whether the intensity of light exceeds a given threshold value. This type of vision system is called a binary vision system. If necessary, it is possible to store different shades of grey in an image, popularly called the grey-scale system. If the computer has a higher main memory and a faster processor, an individual pixel can also store colour information. For the sake of simplicity, let us assume that we will be content with a binary vision system. Now the entire frame of the image will comprise a large number of pixels, each having a binary state, either 0 or 1. Typical pixel arrays are 128×128, 256×256, 512×512, etc.

Edge detection is performed to distinguish the image of the object from its surroundings. Computer programs are used, which identify the contrast in light intensity between pixels bordering the image of the object and resolve the boundary of the object. In order to identify the work part, the pattern in the pixel matrix needs to be compared with the templates of known objects. Since the pixel density is quite high, one-to-one matching at the pixel level within a short time duration demands high computing power and memory. An easier solution to this problem is to resort to a technique known as feature extraction. In this technique, an object is defined by means of its features such as length, width, diameter, perimeter, and aspect ratio. The aforementioned techniques—thresholding and edge detection—enable the determination of an object's area and boundaries.

Image Interpretation

Once the features have been extracted, the task of identifying the object becomes simpler, since the computer program has to match the extracted features with the features of templates already stored in the memory. This matching task is popularly referred to as template matching. Whenever a match occurs, an object can be identified and further analysis can be carried out. This interpretation function that is used to recognize the object is known as pattern recognition. It is needless to say that in order to facilitate pattern recognition, we need to create templates or a database containing features of the known objects. Many computer algorithms have been developed for template matching and pattern recognition. In order to eliminate the possibility of wrong identification when two objects have closely resembling features, feature weighting is resorted to. In this technique, several features are combined into a single measure by assigning a weight to each feature according to its relative importance in identifying the object. This adds an additional dimension in the process of assigning scores to features and eliminates wrong identification of an object.

Generation of Actuation Signals

Once the object is identified, the vision system should direct the inspection station to carry out the necessary action.

Applications of Machine Vision in Inspection

Machine vision systems are used for various applications such as part identification, safety monitoring, and visual guidance and navigation. However, by far, their biggest application is in automated inspection. It is best suited for mass production, where 100% inspection of components is sought. The inspection task can either be in on-line or off-line mode. The following are some of the important applications of machine vision system in inspection:

Dimensional gauging and measurement Work parts, either stationary or moving on a conveyor system, are inspected for dimensional accuracy. A simpler task is to employ gauges that are fitted as end effectors of a transfer machine or robot, in order to carry out gauging, quite similar to a human operator. A more complicated task is the measurement of actual dimensions to determine the dimensional accuracy. This calls for systems with high resolution and good lighting of the scene, which provides a shadow-free image.

Identification of surface defects: Defects on the surface such as scratch marks, tool marks, pores, and blow holes can be easily identified. These defects reveal themselves as changes in reflected light and the system can be programmed to identify such defects.

Verification of holes This involves two aspects. Firstly, the count of number of holes can be easily ascertained. Secondly, the location of holes with respect to a datum can be inspected for accuracy.

Identification of flaws in a printed label Printed labels are used in large quantities on machines or packing materials. Defects in such labels such as text errors, numbering errors, and graphical errors can be easily spotted and corrective action taken before they are dispatched to the customer.