3.1. BASIC CONCEPT OF LASER

After having derived the quantum mechanically correct susceptibility for an inverted atomic system that can provide gain, we can use the two-level model to study the laser and its dynamics. After discussing the laser concept briefly we will investigate various types of gain media, gas, liquid and solid-state, that can be used to construct lasers and amplifiers.

3.1.1 Principle of Lasers

Laser stands for light amplification by stimulated emission of radiation

- Lasers for measurement are low power gas lasers that emit light in the visible range
- Laser light beam is:

– Highly monochromatic - the light has a single wave length

– Highly collimated - the light rays are parallel

- These properties have motivated many applications in measurement and inspection

3.1.2 Advantages of Lasers

1. The installation is easy
2. Accuracy is high
3. It has a long-range optical path.
4. It has high repeatability of displacement measurement
5. There is virtually no wear and tear.
6. As many as six measurements can be made simultaneously by a single laser source.

3.1.3 Disadvantages of Lasers

1. It is expensive
2. The measurement is not in traditional units
3. Conversion instrumentation is required as the measurement is in terms of wavelength.

3.2 Types of Lasers

3.2.1 Gas Lasers

Helium-Neon Laser

The HeNe-Laser is the most widely used noble gas laser. Lasing can be achieved at many wavelengths 632.8nm (543.5nm, 593.9nm, 611.8nm, 1.1523µm, 1.52µm, 3.3913µm). Pumping is achieved by electrical discharge

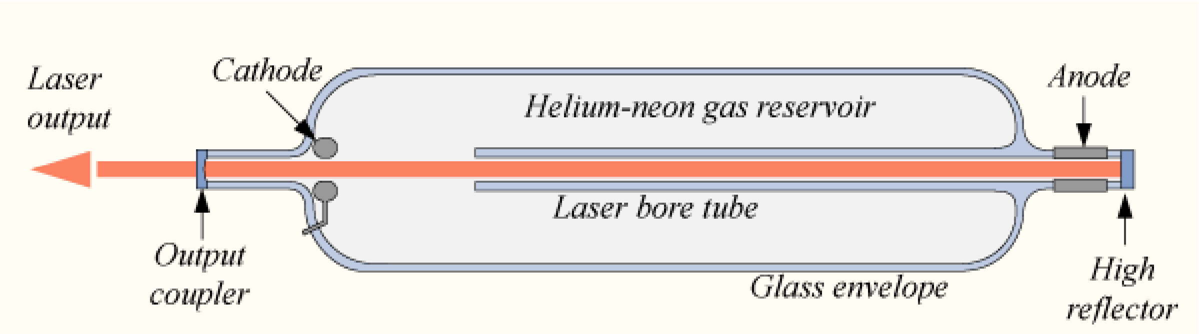

Fig. 3.1 Schematic diagram of a helium–neon laser

[source: https://en.wikipedia.org/wiki/Helium%E2%80%93neon_laser]

The helium is excited by electron impact. The energy is then transferred to Neon by collisions. The first HeNe laser operated at the 1.1523µm line. HeNe lasers are used in many applications such as interferometry, holography, spectroscopy, barcode scanning, alignment and optical demonstrations.

Argon and Krypton Ion Lasers

Similar to the HeNe-laser the Argon ion gas laser is pumped by electric discharge and emits light at wavelength: 488.0nm,514.5nm,351nm,465.8nm, 472.7nm, 528.7nm. It is used in applications ranging from retinal phototherapy for diabetes, lithography, and pumping of other lasers. The Krypton ion gas laser is analogous to the Argon gas laser with wave length: 416nm, 530.9nm, 568.2nm, 647.1nm, 676.4nm, 752.5nm, 799.3nm.

Pumped by electrical discharge. Applications range from scientific research. When mixed with argon it can be used as "white-light" lasers for light shows.

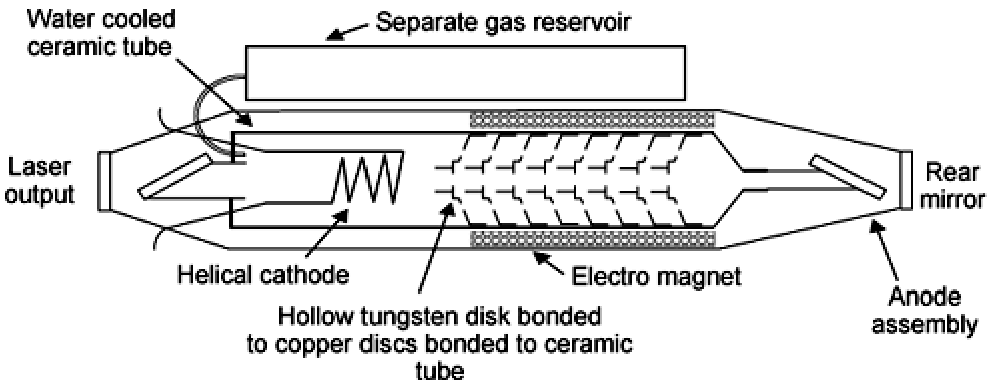

Fig. 3.2 Argon Ion Lasers

[source: https://www.twi-global.com/technical-knowledge/faqs/faq-what-is-an-argon-ion-laser]

Carbon Lasers

In the carbon dioxide (CO2) gas laser the laser transistions are related to vibrational rotational excitations. CO2 lasers are highly efficient approaching 30%. The main emission wavelengths are 10.6µm and 9.4µm. They are pumped by transverse (high power) or longitudinal (low power) electrical discharge. It is heavily used in the material processing industry for cutting, and welding of steel and in the medical area for surgery. Carbon monoxide (CO) gas laser: Wavelength 2.6 - 4µm, 4.8 - 8.3µm pumped by electrical discharge. Also used in material processing such as engraving and welding and in photoacoustic spectroscopy. Output powers as high as 100kW have been demonstrated.

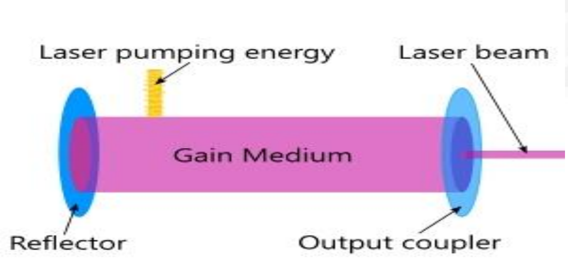

Fig. 3.3 Carbon Lasers

[source:https://www.globalspec.com/learnmore/optical_components_optics/lasers/carbon_dioxide_lasers]

Excimer Lasers:

Chemical lasers emitting in the UV: 193nm (ArF), 248nm (KrF), 308nm (XeCl), 353nm (XeF) excimer (excited dimer). These are molecules that exist only if one of the atoms is electronically excited. Without excitation the two atoms repell each other. Thus, the electronic ground state is not stable and is therefore not populated, which is ideal for laser operation. These lasers are used for ultraviolet lithography in the semiconductor industry and laser surgery.

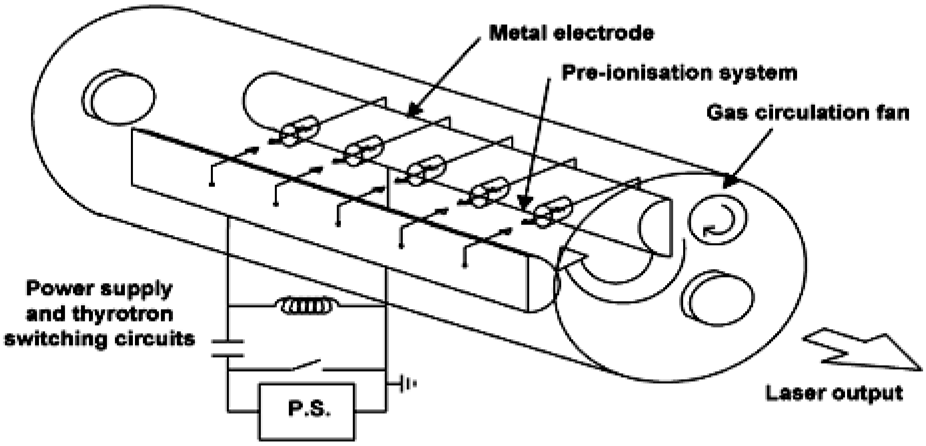

Fig. 3.4 Excimer Lasers

[source: https://www.twi-global.com/technical-knowledge/faqs/faq-what-is-an-excimer-laser]

3.2.2 Dye Lasers

The laser gain medium are organic dyes in solution of ethyl, methyl alcohol, glycerol or water. These dyes can be excited by optically with Argon lasers for example and emit at 390-435nm (stilbene), 460-515nm (coumarin 102), 570-640 nm (rhodamine 6G) and many others. These lasers have been widely used in research and spectroscopy because of there wide tuning ranges. Un fortunately, dyes are carcinogenic and as soon as tunable solid state laser media became available dye laser became extinct.

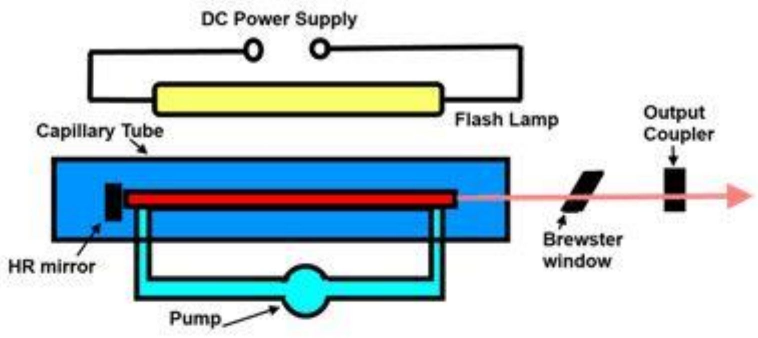

Fig. 3.5 Dye Lasers

[source: https://www.daenotes.com/electronics/microwave-radar/dye-laser#sthash.WbDyZ7bC.dpbs]

3.2.3 Solid-State Lasers

Ruby Laser

The first laser was indeed a solid-state laser: Ruby emitting at 694.3nm. Ruby consists of the naturally formed crystal of aluminium oxide (Al2O3) called corundum. In that crystal some of Al^{3+} ions are replaced by Cr^{3+} ions. It's the chromium ions that give Ruby the pinkish colour, i.e., its flourescence, which is related to the laser transisitons.

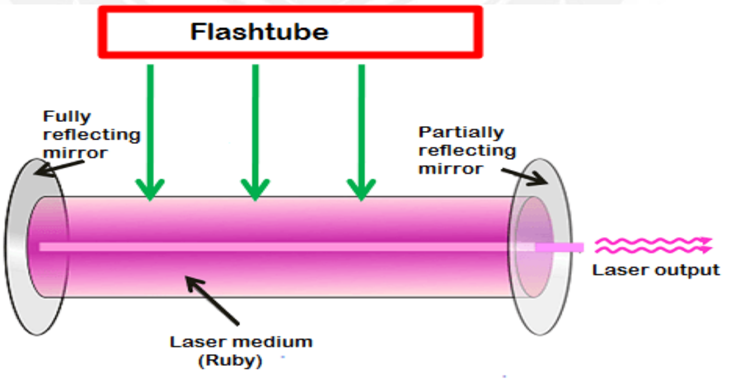

Fig. 3.6 Ruby Laser

[source: https://www.physics-and-radio-electronics.com/physics/laser/rubylaserdefinitionconstructionworking.html]

Neodymium YAG (Nd: YAG)

Neodymium YAG consists of Yttrium-Aluminium-Garnet (YAG) $Y_3Al_5O_{12}$ in which some of the Y^{3+} ions are replaced by Nd^{3+} ions. Neodymium is a rare earth element, where the active electronic states are shielded inner 4f states. Nd: YAG is a four-level laser. The main emission of Nd: YAG is at 1.064µm. Another line with considerable less gain is at 1.32µm. Initially Nd: YAG was flashlamp pumped. Today, much more efficient pumping is possible with laser diodes and diode arrays. Diode pumped versions which can be very compact and efficient become a competition for the CO_2 laser in material processing, range finding, surgery, pumping of other lasers in combination with frequency doubling to produce.

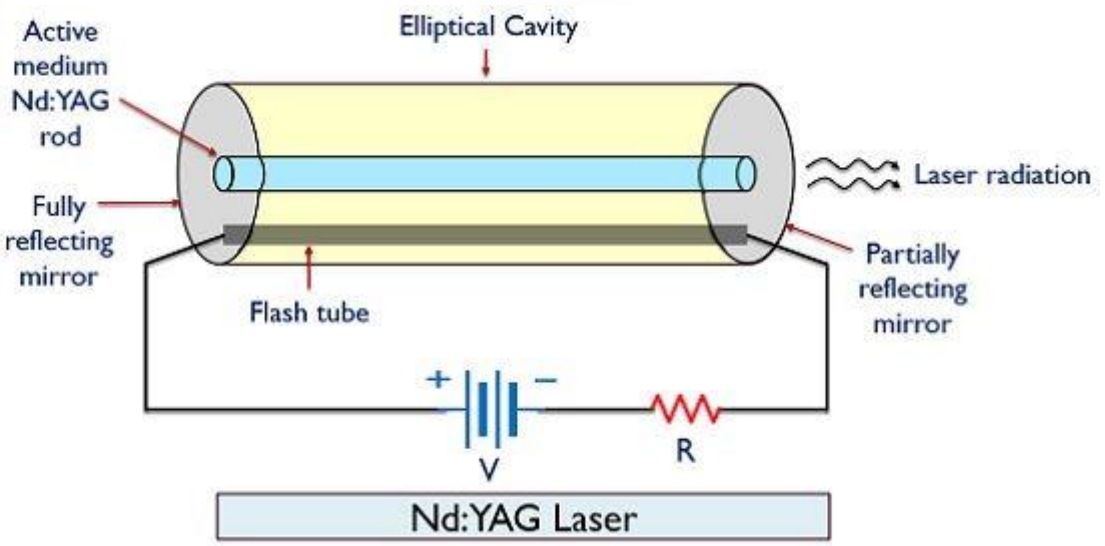

Fig. 3.7 Neodymium YAG laser

[source: https://circuitglobe.com/ndyag-laser.html]

Ytterbium YAG

Ytterbium YAG is a quasi-three level laser, see Figure 303 emitting at 1.030µm. The lower laser level is only 500-600cm1 (60meV) above the ground state and is therefore at room temperature heavily thermally populated. The laser is pumped at 941 or 968nm with laser diodes to provide the high brightness pumping needed to achieve gain.

However, Yb:YAG has many advantages over other laser materials:

- Very low quantum defect, i.e. difference between the photon energy necessary for pumping and photon energy of the emitted radiation, (hfP - hfL) /hfP ˜ 9%.

- long radiative lifetime of the upper laser level, i.e. much energy can be stored in the crystal.
- high doping levels can be used without upper state lifetime quenching
- broad emission bandwidth of Δ_{fFWHM} =2.5THz enabling the generation of subpicosecond pulses.
- with cryogenic cooling Yb: YAG becomes a four-level laser.

Due to the low quantum defect and the good thermal properties of YAG, Yb:YAG lasers approaching an optical to optical efficiency of 80% and a wall plug efficiency of 40% have been demonstrated.

Titanium Sapphire (Ti:sapphire)

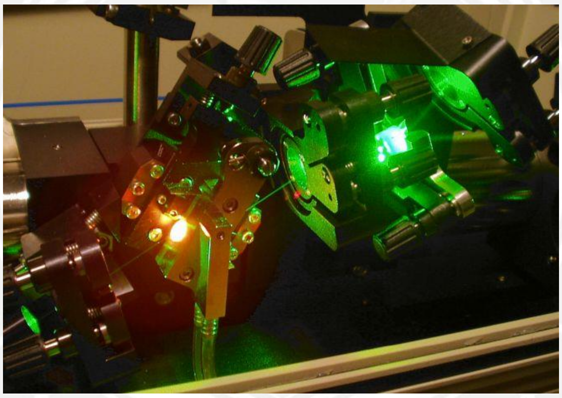

Fig. 3.8 Titanium Sapphire laser

[source: https://en.wikipedia.org/wiki/File:Titanium_sapphire_oscillator.jpg]

In contrast to Neodymium, which is a rare earth element, Titanium is a transition metal. The Ti^{3+} ions replace a certain fraction of the Al^{3+} ions in sapphire (Al2O3). In transistion metal lasers, the laser active electronic states are outer 3s electrons which couple strongly to lattice vibrations. These lattice vibrations lead to strong line broadening. Therefore, Ti:sapphire has an extremely broad amplification linewidth Δf_{FWHM} ≈100THz. Ti:sapphire can provide gain from 650-1080nm. Therefore, this material is used in today's highly-tunable or very short pulse laser systems and amplifiers. Once Ti:sapphire was developed it rapidly replaced the dye laser systems.

3.2.4 Semiconductor Lasers

An important class of solid-state lasers are semiconductor lasers. Depending on the semiconductor material used the emission wavelength can be further refined by using band structure engineering, 0.4 µm (GaN) or 0.63-1.55 µm (AlGaAs, InGaAs, InGaAsP) or 3-20 µm (lead salt). The AlGaAs based lasers in the wavelength range 670nm-780 nm are used in compact disc players and therefore are the most common and cheapest lasers in the world. In the semiconductor laser the electronic band structure is exploited, which arises from the periodic crystal potential, see problem set.

There is usually a highest occupied band, the valence band and a lowest unoccupied band the conduction band. Electronics states in a crystal can usually be characterized by their quasi-momentum k.

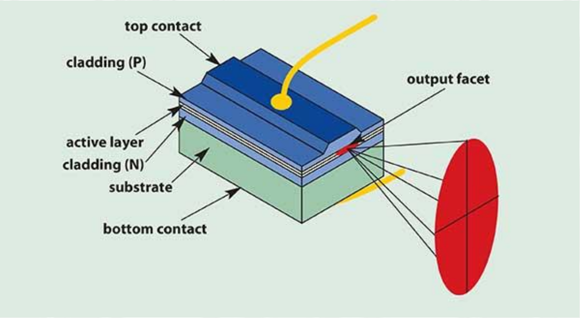

Fig. 3.9 Semiconductor Lasers

[source:https://www.photonics.com/images/Web/Articles/2006/4/13/SemiconductorLasers_JDSU_Figure1.jpg]

3.2.5 Quantum Cascade Lasers

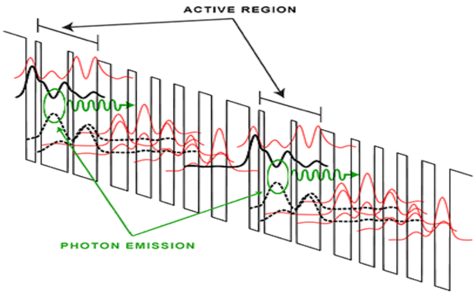

Fig. 3.10 Semiconductor Lasers

[source: https://www.teamwavelength.com/quantum-cascade-laser-basics/]

A new form of semiconductor lasers was predicted in the 70’s by the two russian physicists Kazarinov and Suris that is based only on one kind of electrical carriers. These are most often chosen to be electrons because of there higher mobility. This laser is therefore a unipolar device in contrast to the conventional semiconductor laser that uses both electrons and holes. The transitions are intraband transistions.

3.2 APPLICATIONS OF LASER IN MEASUREMENT

3.2.1 LASER TELEMETRIC SYSTEM

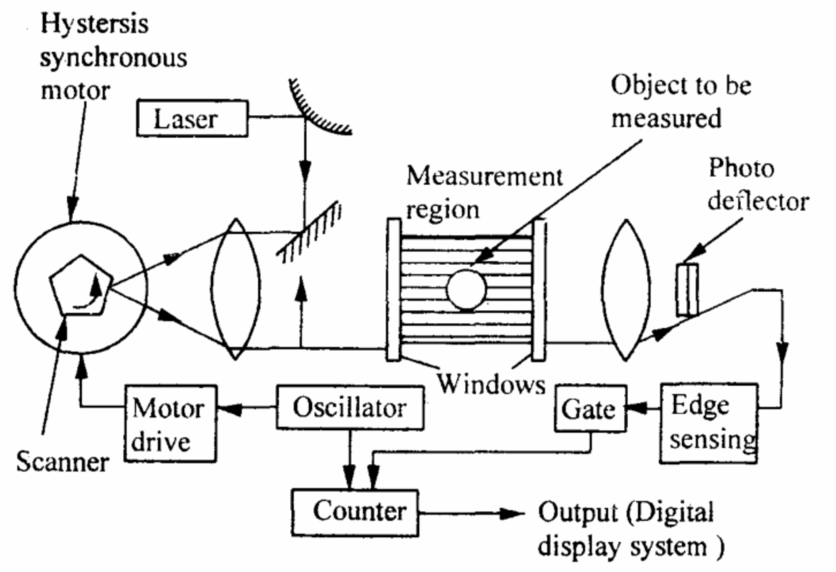

Fig. 3.11 Laser Telemetric System

[source: http://what-when-how.com/metrology/laser-telemetric-system-metrology/]

Construction:

The Laser telemetric system consist of three components.

- Transmitter
- Receiver
- Processor electronics

Laser telemetric system is a non-contact gauge that measures with a collimated laser beam. It measures at the rate of 150 scans per second. It basically consists of three components, a transmitter, receiver and processor electronics. The transmitter module produces a collimated parallel scanning laser beam moving at a high, constant, linear speed. The scanning beam appears as a red line. The receiver module collects and photoelectrically senses the laser light transmitted past the object being measured. The processor electronics takes the received signals to convert them to a convenient form and displays the dimension being gauged.

The transmitter contains a low-power helium-neon gas laser and its power supply, a specially designed collimating lens, a hysteresis synchronous motor, a mutli-faceted reflector prism, a synchronous pulse photodetector and a protective replaceable window. The high speed of scanning permits on-line gauging and thus it is possible to detect changes in dimensions when components are moving or a continuous product such as in rolling process moving at very high speed. There is no need of waiting or product to cool for taking measurements.

This system can also be applied on production machines and control them with closed feedback loops. Since the output of this system is available in digital form, it can run a process controller, limit alarms can be provided and output can be taken on digital printer. It is possible to write programs for the microprocessor to take care of smoke, dust and other airborne interference around the workpiece being measured.

ADVANTAGES

- ❖ It is possible to detect changes in dimensions when the product is in continuous processes.
- ❖ It can be applied on production machines and controlled then with closed feedback loops.

3.2.2 Laser Scanning Gauge

The scanning laser gauge is used for dimensional measurements.

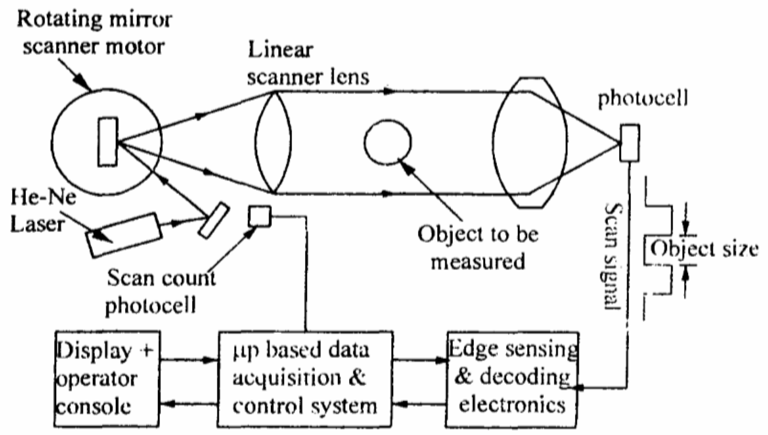

Fig. 3.12 Laser Telemetric System

[source: http://what-when-how.com/metrology/laser-inspection-metrology/]

Metrology lasers are low-power instruments. Most are helium-neon continuous-wave output lasers that emit visible or infrared light. He-Ne lasers produce light at a wavelength of 6328 A (0.6 pi) that is in phase, coherent, and a thousand times more intense than any other monochromatic source.

Laser inspection systems enable measurement of a part as it is produced, thus permitting 100% quality. Laser systems have wide dynamic range, low optical cross talk, and high contrast.

Lasers find applications in dimensional measurements and surface inspection because of the properties of laser light (bright, unidirectional, collimated beam, with a high degree of temporal and spatial coherence). These are useful where precision, accuracy, rapid non-contact gauging of soft, delicate, hot or moving parts is called for.

Various technique for dimensional measurements are:

It basically utilises a transmitter, receiver and processor electronics. A thin band of scanning laser light is made to pass through a linear scanner lens to render it parallel beam. The object placed in a parallel beam, casts a time-dependent shadow. Signals from the light entering the photo cell (receiver) are processed by a microprocessor to provide display of the dimension represented by the time difference between the shadow edges. It can provide results to an accuracy of + 0.25 um for 10-50 mm diameter objects. It can be used for objects 0.05 mm to 450 mm diameter and offers repeatability of 0.1 um.

3.2.3 PHOTODIODE ARRAY IMAGE

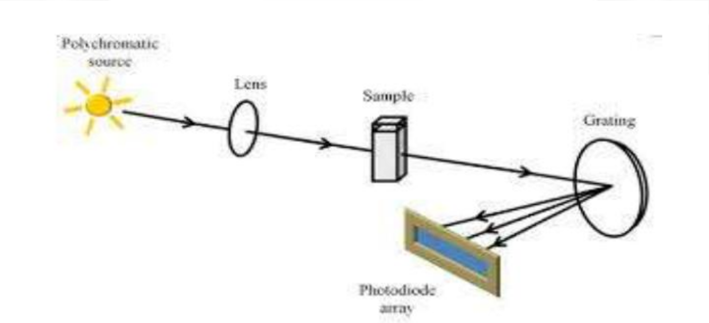

Fig. 3.13 Laser Telemetric System

[source: http://what-when-how.com/metrology/laser-inspection-metrology/]

In this method, shadow of stationary part is projected on a solid-state diode array image sensor. The system comprises of laser source, imaging optics, photodiode array, and signal processor and display unit. For large parts, two arrays, one for each edge are used. Accuracies as high as + 0.05 um have been achieved.

A Photodiode Array Detector is a microprocessor controlled multi-channel detector that permits simultaneous access to spectral data for several wavelengths simultaneously. In comparison the conventional UV-Visible detector has only a single channel detector.

Simultaneous multi-wavelength measurement

In a conventional spectrophotometer a single wavelength is recorded at any given point of time. On the other hand all wavelengths can be measured simultaneously in the diode array detector and this feature is a great time saver when several wavelengths are to be monitored simultaneously.

Wavelength precision

The required wavelength is selected on a conventional spectrophotometer either manually or using a stepper motor. On the other hand in the photodiode array data is acquired at each wavelength simultaneously. This eliminates repeatability errors that result from mechanical wear of moving parts.

High sensitivity

Diode array systems have fewer optical surfaces as a result of which the light throughput is high and results in improved sensitivities. An added benefit is time averaging feature to get several fold improvements of spectral sensitivity.

Minimal Stray Light

A photodiode array spectrophotometer has reverse optics design which minimizes stray light which is a common interfering component in conventional spectrophotometers. In case of photodiode array system, the sample is placed before the polychromator (reverse optics) whereas in case of conventional spectrophotometer sample is positioned after the monochromator. As the measurements are unaffected by stray light observations can be made with the sample chamber open without interference from outside light. This feature also permits analysis on a wider range of sample sizes and use of special sampling accessories

Ruggedness

The reliability and ruggedness is higher for photodiode array detector due to absence of moving parts and mechanical simplicity. This also eliminates virtually need for maintenance or re-calibration. As photodiode array detector is a solid-state device it is more reliable and secure than the photomultiplier tube. A polychromator gives consistent performance as the light dispersion element is locked in its position whereas in case of conventional spectrophotometer scanning requires movement of the grating inside the monochromator.

3.2.4 Diffraction Pattern Technique

These are used to measure small gaps and small diameter parts. In this method, a parallel coherent laser beam is diffracted by a small part, and the resultant pattern is focussed by a lens on a linear diode array. Since diffraction is not suitable for diameters larger than a few millimeters, its use is restricted to small wires, etc. The measurement accuracy is more for smaller parts. The distance between the alternating light and dark bands in the diffraction pattern is a direct function of the wire diameter, wavelength of laser beam, and the focal length of the lens.

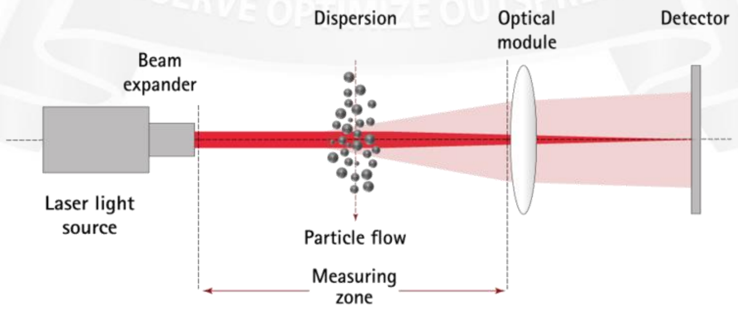

Fig. 3.14 Diffraction Pattern Technique

[source: https://www.sympatec.com/en/particle-measurement/sensors/laser-diffraction/]

3.2.5 Laser Triangulation Sensors

In this sensor a finely focused laser of light is direct at the part surface and this light comes from the laser source.

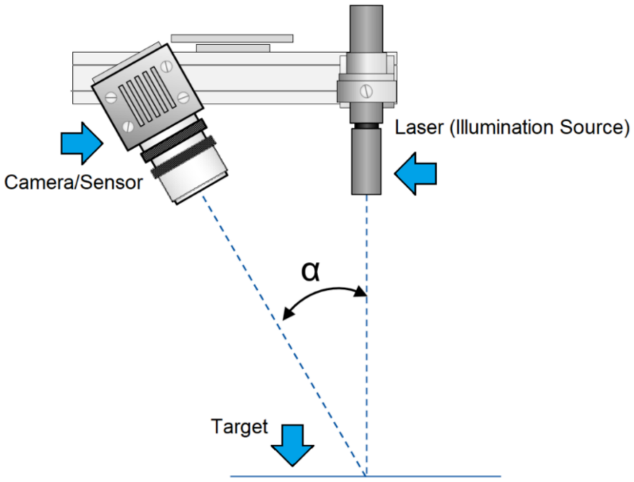

Fig. 3.15 Laser Triangulation Sensors

[source: https://www.movimed.com/knowledgebase/what-is-laser-triangulation/]

Laser Triangulation is a machine vision technique used to capture 3-dimensional measurements by pairing a laser illumination source with a camera. The laser beam and the camera are both aimed at the inspection target, however by adopting a known angular offset (α) between the laser source and the camera sensor, it is possible to measure depth differences using trigonometry.

The red, green, and blue dotted lines in Figure 2 illustrate how the reflected laser light will strike different sensor locations, depending on the distance between the laser source and the inspection target (or "surface"). Notice that the position where the reflected laser light strikes the sensor's surface is dependent on the vertical offset of the target from the laser/camera assembly. In other words, as the distance between the laser light source and inspection point changes, so changes the location on the sensor where the light is detected. Changes from the nominal vertical distance will produce proportional changes in position (d') at the sensor. Larger changes in vertical distance will result in a larger positional deflection at the sensor.

Advantages:

- Quick measurement of deviations is due to change in surface.
- it can perform automatic calculation on shell metal stampings.

Two- frequency laser interferometer

This consists of two frequency laser head, beam directing and splitting optics, measurement optics, receivers, and wavelength compensators and electronics. It is ideally suited for measuring linear positioning straightness in two planes, pitch and yaw.

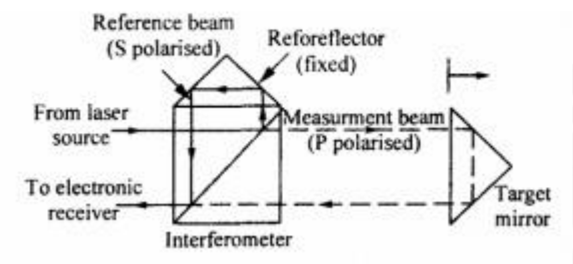

Fig. 3.16 Two- frequency laser interferometer

[source: https://www.brainkart.com/article/Use-of-Laser_5836/]

The two-frequency laser head provides one frequency with P-polarization and another frequency with S-polarization. The laser beam is split at the polarizing beam splitter into its two separate frequencies. The measuring beam is directed through the interferometer to reflect off a target mirror or retro reflector attached to the object to be measured. The reference beam is reflected from fixed retro reflector. The measurement beam on its return path recombines with the reference beam and is directed to the electronic receiver.

Gauging wide diameter from the diffraction pattern formed in a laser

Figure shows a method of measuring the diameter of thin wire using the interference fringes resulting from diffraction of the light by the wire in the laser beam. A measure of the diameter can be obtained by moving the photo detector until the output is restored to its original value. Variation in wire diameter as small as 0.2% over wire diameter from 0.005 to 0.2mm can be measured.

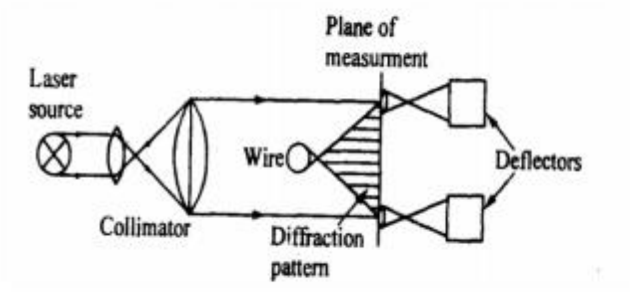

Fig. 3.16 Diffraction Pattern

[source: https://www.brainkart.com/article/Use-of-Laser_5836/]

Figure shows the length measurement by fringe counting. The laser output, which may be incoherent illumines three slits at a time in the first plane which form interference fringes. The movement can be determined by a detector. The total number of slits in the first plane is governed by the length over which measurement is required.

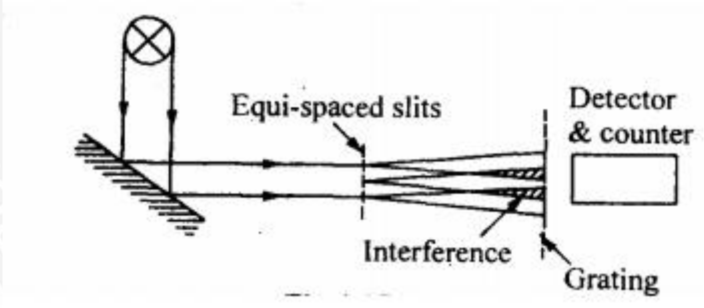

Fig. 3.16 Laser interferometer

[source: https://www.brainkart.com/article/Use-of-Laser_5836/]

The spacing between the slits and distance of the slit to the plane of the grating depend on the wavelength of the light used.

LASER INTERFEROMETERS

In recent times, laser-based interferometers are becoming increasingly popular in metrology applications. Traditionally, lasers were more used by physicists than engineers, since the frequencies of lasers were not stable enough. However now, 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. However, even to this day, laser-based instruments are extremely costly and require many accessories, which hinder 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.

In interferometry, laser light exhibits properties similar to that of any ‘normal’ light. It can be represented by a sine wave whose wavelength is the same for the same colours and amplitude is a measure of the intensity of the laser light. From the measurement point of view, laser interferometry can be used for measurements of small diameters as well as large displacements. In this section, we present a simple method to measure the latter aspect, which is used for measuring machine slideways. The laser-based instrument is shown in Fig. 7.19. 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.

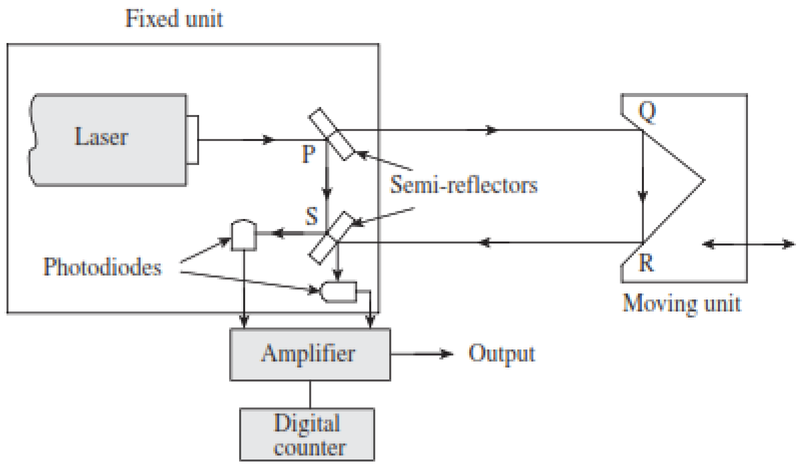

Fig. 3.17 Fringe Pattern

[source: “Engineering Metrology & Measurements”, N.V. Raghavendra., page-181]

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.

It must have now become obvious to you that 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 millimetres. The purpose of using a second photodiode is to sense the direction of movement of the slide.

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.

Components Laser Interferometry

i. Two frequency Laser sources
ii. Optical elements
iii. Laser head’s measurement receiver
iv. Measurement display

i. Two frequency Laser sources

It is generally He-Ne type that generates stable coherent light beam of two frequencies, one polarized vertically and another horizontally relative to the plane of the mounting feet. Laser oscillates at two slightly different frequencies by a cylindrical permanent magnet around the cavity. The two components of frequencies are distinguishable by their opposite circular polarization. Beam containing both frequencies passes through a quarter wave and half wave plates which change the circular polarizations to linear perpendicular polarizations, one vertical and other horizontal. Thus, the laser can be rotated by 90°about the beam axis without affecting transducer performance. If the laser source is deviated from one of the four optimum positions, the photo receiver will decrease. At 45° deviation the signal will decrease to zero.

ii. Optical elements

a) Beam splitter

Sketch shows the beam splitters to divide laser output along different axes. These divide the laser beam into separate beams. To avoid attenuation, it is essential that the beam splitters must be oriented so that the reflected beam forms a right angle with the transmitted beam. So that these two beams: are coplanar with one of the polarisation vectors of the input form.

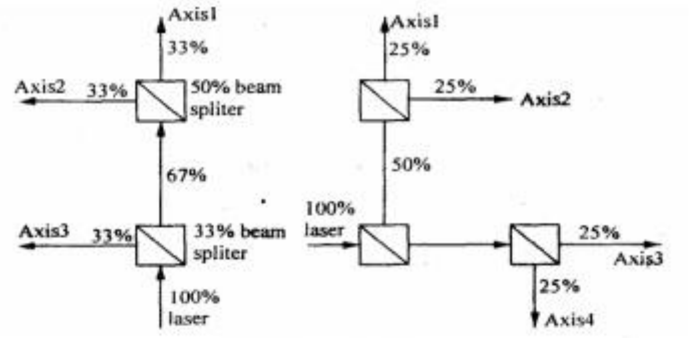

Fig. 3.18 Beam splitter

[source: https://www.brainkart.com/article/Laser-Interferometry_5837/]

b) Beam benders

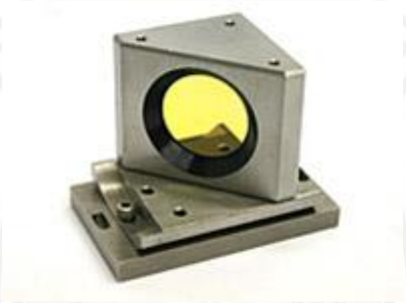

Fig. 3.19 Beam splitter

[source: http://www.motionxcorp.com/beam-benders.html]

These are used to deflect the light beam around corners on its path from the laser to each axis. These are actually just flat mirrors but having absolutely flat and very high reflectivity. Normally these are restricted to 90° beam deflections to avoid disturbing the polarizing vectors.

c) Retro reflectors

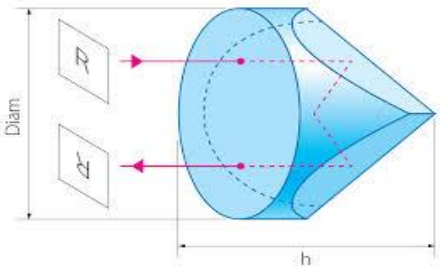

Fig. 3.20 Beam splitter

[source: https://www.altechna.com/products/corner-cube-retroreflector/]

These can be plane mirrors, roof prism or cube corners. Cube corners are three mutually perpendicular plane mirrors and the reflected beam is always parallel to the incidental beam. Each ACLI transducers need two retro reflectors. All ACLI measurements are made by sensing differential motion between two retro reflectors relative to an interferometer. Plane mirror used as retro reflectors with the plane mirror interferometer must be flat to within 0.06 micron per cm.

(iii) Laser head’s measurement receiver

During a measurement the laser beam is directed through optics in the measurement path and then returned to the laser head is measurement receiver which will detect part of the returning beam and a doppler shifted frequency component.

(iv) Measurement display

It contains a microcomputer to compute and display results. The signals from receiver and measurement receiver located in the laser head are counted in two separate pulse converter and subtracted. Calculations are made and the computed value is displayed. Other input signals for correction are temperature, co-efficient of expansion, air velocity etc., which can be displayed.

TYPES OF LASER INTERFEROMETER

The following are the types of laser interferometer:

i. AC Laser Interferometer
ii. DC Laser Interferometer

i) AC Laser Interferometer

It is possible to maintain the quality of interference fringes over longer distance when lamp is replaced by a laser source. Laser interferometer uses AC laser as the light source and the measurements to be made over longer distance. Laser is a monochromatic optical energy, which can be collimated into a directional beam AC. Laser interferometer (ACLI) has the following advantages.

- High repeatability
- High accuracy
- Long range optical path
- Easy installations
- Wear and tear

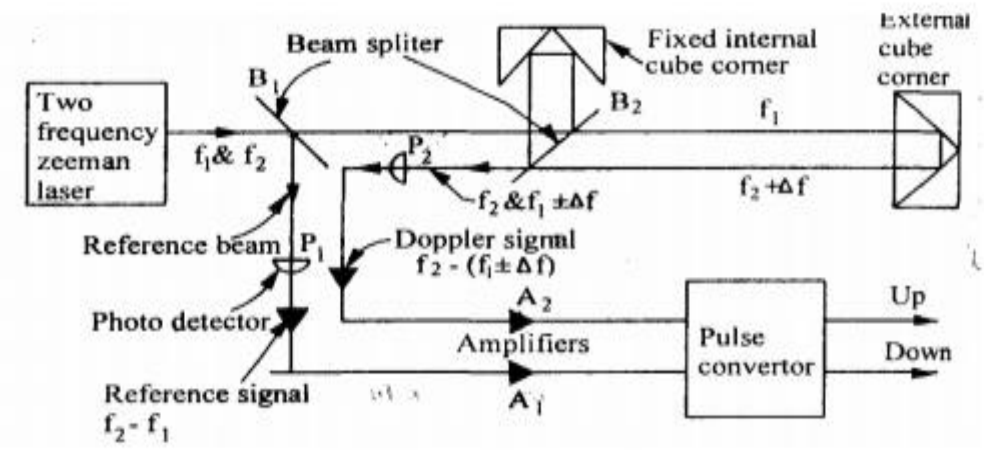

Fig. 3.21 **AC Laser Interferometer**

[source: https://www.brainkart.com/article/Laser-Interferometer_5838/]

Schematic arrangement of laser interferometer is shown in fig. Two-frequency Zeeman laser generates light of two slightly different frequencies with opposite circular polarisation. These beams get split up by beam splitter B One-part travels towards B and from there to external cube corner here the displacement is to the measured.

This interferometer uses cube corner reflectors which reflect light parallel to its angle of incidence. Beam splitter B2 optically separates the frequency J which alone is sent to the movable cube corner reflector. The second frequency from B2 is sent to a fixed reflector which then re-joins f1 at the beam splitter B2 to produce alternate light and dark interference flicker at about 2 Mega cycles per second. Now if the movable reflector moves, then the returning beam frequency Doppler-shifted slightly up Thus the light beams moving towards photo detector P2 have frequencies f2 and (f1 ± Δf1) and

P2 changes these frequencies int signal from beam splitter B2 and changes the reference beam frequencies f1 and f2 into electrical signal. An AC amplifier A separates frequency. Difference signal f2 –f1 and A2 separates frequency difference signal. The pulse converter extracts i. one cycle per half wavelength of motion. The up-down pulses are counted electronically and displayed in analog or digital form.

Types of AC Laser Interferometer

a) Standard Interferometer

- Least expensive.
- Retro reflector for this instrument is a cube corner.
- Displacement is measured between the interferometer and cube corner.

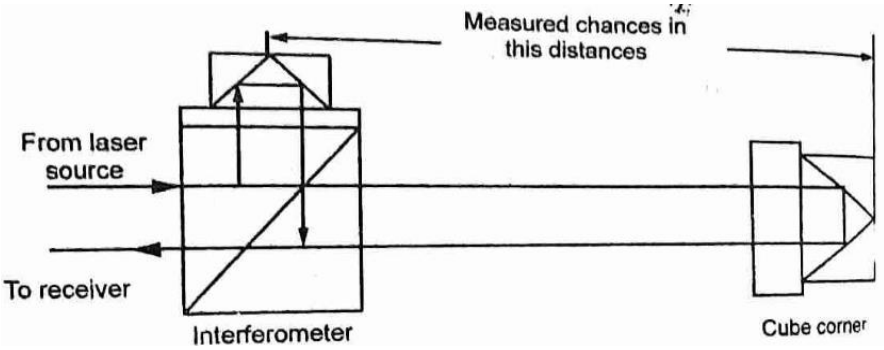

Fig. 3.22 Standard Interferometer

[source: https://www.brainkart.com/article/Laser-Interferometry_5837/]

b) Signal beams Interferometer

- Beam traveling between the interferometer and the retro reflector.
- Its operation same as standard interferometer.
- The interferometer and retro reflector for this system are smaller than the standard system.
- Long range optical path
- Wear and tear.

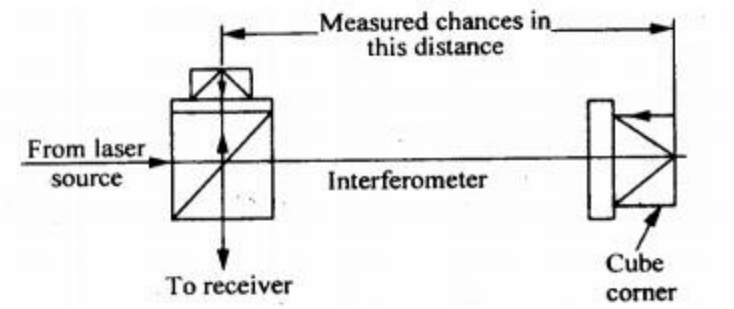

Fig. 3.23 Standard Interferometer

[source: https://www.brainkart.com/article/Laser-Interferometry_5837/]

ii) DC Laser Interferometer

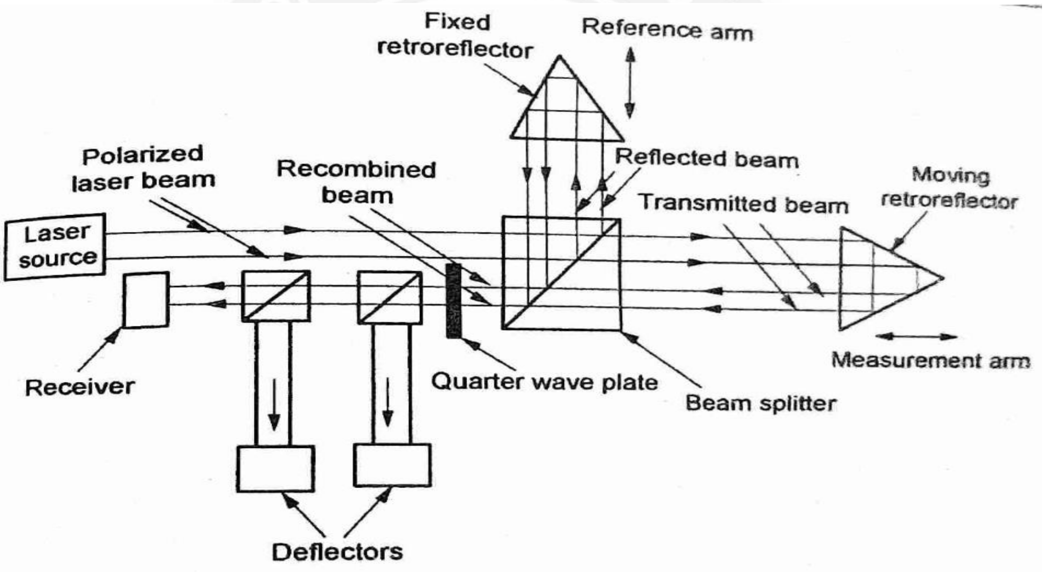

Fig. 3.24 DC Laser Interferometer

[source: http://what-when-how.com/metrology/interferometers-metrology/]

It is much improved system over the Michelson simple interferometer. It uses a single frequency circular polarised laser beam. On reaching the polarising beam splitter, the beam splits into two components, the reflected beam being vertically polarised light and the transmitted beam being horizontally polarised light. These two beams referred to as reference arm and measurement arm respectively travel to their retroreflectors and are then reflected back towards the beam splitter. The recombined beam at beam splitter consists of two superimposed beams of different polarisation ; one component vertically polarised having travelled around reference arm and other component horizontally polarised having travelled around the measurement arm. These two beams being differently polarised do not interfere. The recombined beam then passes through a quarter waveplate which causes the two beams to interfere with one another to produce a beam of plane polarised light. The angular orientation of the plane of this polarised light depends on the phase difference between the light in the two returned beams.

The direction of plane of polarisation spin is dependent on the direction of movement of the moving retroreflector. The beam after quarter waveplate is split into three polarisation sensitive detectors. As the plane of polarised light spins, each detector produces a sinusoidal output wave from. The polarisation sensitivity of the detectors can be set so that their outputs have relative phases of 0°, 90°, and 180°. The outputs of three detectors can be used to distinguish the direction of movement and also the distance moved by the moving retroreflector attached to the surface whose displacement is to be measured.

For linear measurements (positional accuracy or velocity), the retroreflector is attached to the body moving along the linear axis. For angular measurement. For pitch and yaw), the angular beam splitter is placed in the path between the laser head and the angular reflector. In this way it is possible to measure flatness, straightness, rotatory axis calibration. Arrangements also need to be made for environmental compensation because the refractive index of the air varies with temperature, pressure and humidity. Heterodyne interferometer, an a.c. device avoids all the problems encountered in above d.c. device, i.e., effect of intensity level change of source, fringe contrast changes and d.c. level shifts which can cause fringe miscounting. Interferometry is now an established and well-developed technique for high accuracy and high-resolution measurement.

Uses of Laser Interferometer:

- Since laser interferometer produces very thin, straight beam, they are used measurement and alignment in the production of large machines.
- They are also used to calibrate precision machine and measuring devices.
- They can also be used to check machine setup. A laser beam is projected against the work and measurements are made by the beam and displayed on a digital readout panel.

- Because of their very thin, straight beam characteristics, lasers are extensively used in constructions and surveying. They are used to indicate the exact location for positioning girders on a tall building or establishing directional lines for a tunnel being constructed under a river.
- Laser interferometers can also used in a glass feature.

Other types of interferometer

The following are the other types of interferometer:

i) Michelson interferometer
ii) Twyman-green specialisation of Michelson interferometer
iii) Dual frequency laser interferometer

Michelson interferometer

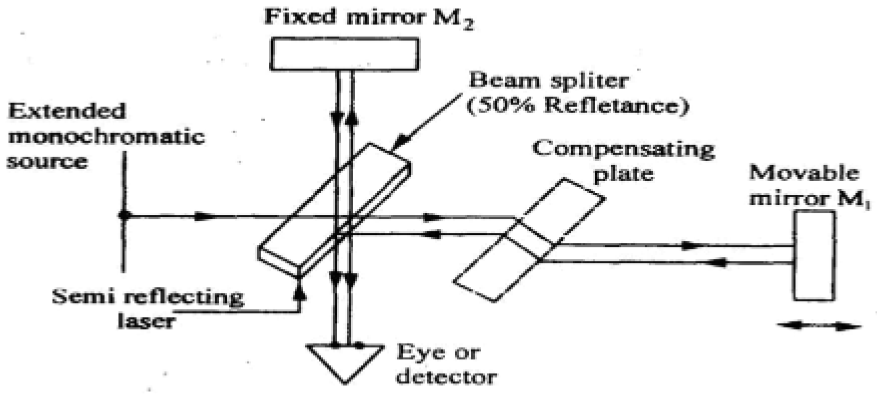

Fig. 3.24 Michelson interferometer

[source: Metrology and Measurements, Dr. G. K Vijayaraghavan pg.no. 3.26]

Michelson interferometer consists of a mono chromatic light source a beam splitter and two mirrors. The schematic arrangement of Michelson interferometer is shown in fig. The monochromatic light falls on a beam splitter, which splits the light into two rays of equal intensity at right angles. One ray is transmitted to mirror M1 and other is reflected through beam splitter to mirror M2. From both these mirrors, the rays are reflected back and these return at the semi reflecting surface from where they are transmitted to the eye. Mirror M2 is fixed and mirror M1 is movable. If both the mirrors are at same distance from beam splitter, then light will arrive in phase and observer will see bright spot due to constructive interference. If movable mirror shifts by quarter wavelength, then beam will return to observer 1800 out of phase and darkness will be observed due to destructive interference.

Each half - wavelength of mirror travel produces a change in them measured optical path of one wave length and the reflected beam from the moving mirror shifts through 360° phase change. When the reference beam reflected from the fixed mirror and the beam reflected from the moving mirror re-join at the beam splitter, they alternately reinforce and cancel each other as the mirror moves. Each cycle of intensity at the eye represents l/2 of mirror travel. When white light source is used then a compensator plate is introduced in each of the path of mirror M1 So that exactly the same amount of glass is introduced in each of the path.

To improve the Michelson interferometer

- Use of laser the measurements can be made over longer distances and highly accurate measurements when compared to other mono chromatic sources.
- Mirrors are replaced by cube - corner reflector which reflects light parallel to its angle of incidence.
- Photo cells are employed which convert light intensity variation in voltage pulses to give the amount and direction of position change.

Dual frequency Laser Interferometer

This instrument is used to measure displacement, high-precision measurement of lengths, angles, speeds and refractive indices as well as derived static and dynamic quantities. It operates on heterodyne principle. The two resonator modes (frequencies ft and ft) are generated in a laser tube such that ft – ft = 640 MHz. These are controlled so that their maxima are symmetrical to the atomic transition. This permits a long reliable stability. The frequency stability of He-Ne laser is responsible for outstanding performance of the interferometer.

An amplitude beam splitter branches off part of the laser output create a reference beam, which an optical fibre cable relays to a photodetector

1. This detects the beat signal of the 640 MHz frequency difference produced by the heterodyning of the two modes. The other portion of the light serves as measuring beam. Via an interferometer arrangement it is directed to a movable measuring mirror and a stationary reference mirror, which reflects it on to a photo-detector

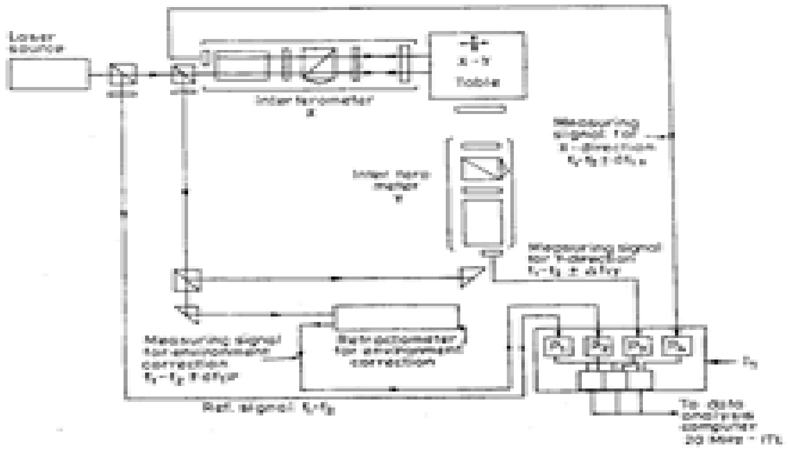

Fig. 3.25 Dual frequency Laser Interferometer

[source: https://what-when-how.com/metrology/heterodyne-interferometry-technique-metrology/]

2. The two frequencies in the measuring beam are separated by a polarisation- sensitive beam splitter so that the measuring mirror receives light of frequency $\bar{\imath}$ only, whereas the light that strikes the reference consists exclusively of frequency f_2. With the measuring mirror at rest, detector 2 also senses the laser differential frequency of i – f_2 = 640 MHz. If the measuring mirror is being displaced at a speed v, the partial beam of frequency/i reflected by it is subjected to a Doppler shift dfx; where dfx = (2v)/Xx- Accordingly, detector 2 now receives a measuring frequency of f_x-f_2± dfx (+ dfx or – dfx) depending on the direction of movement of the measuring mirror. The reference frequency $\bar{f}$—fi ana the measuring frequency $\bar{f}$—f%± dfx are compared with each other by an electronic counting chain. The result is the frequency shift ± dfx due to the Doppler effect, a measure of the wanted displacement of the measuring mirror. In a fast, non-hysteric comparator, the

Pl = Photo detector for reference signal

P2, P3 and P4 = photo detectors for measuring

Ix = Basic Instrument signals with HF signal processing and interpolation facilities.

Doppler frequency d$\bar{f}$is digitised and then fed to a counter, which registers the number of zero passages per unit time.

The forward and return movements of the measuring mirror can be distinguished by outcoupling the measuring signal $\bar{i}$ – f_2 + dfx at ‘n’ phase angles, via a delay line and feeding to ‘re’ mixers. The mixers are connected with the reference signal $\bar{f}$—f_2 (common feeding point for all mixers). Thus, n Doppler frequencies get shifted in phase by at the mixer outputs. They are symmetrical relative to zero. After comparison they are made available to low-frequency counting logic as TTL signals. The n phase angles and their tolerances are implemented by the geometry of the delay line. This system can be used for both incremental displacement and angle measurements. Due to large counting range, it is possible to attain a resolution of 2 nm in 10 m measuring range. Means are also provided to compensate for the influence of ambient temperature, material temperature, atmospheric pressure and atmospheric humidity fluctuations.

Twyman–Green Interferometer:

Twyman–Green interferometers, named after Frank Twyman and Arthur Green, are interferometers which are used for characterizing optical surfaces.

The optical setup is similar to that of a Michelson interferometer, but a Twyman–Green interferometer works with collimated beams which are expanded to a substantial diameter. In the simplest case, such an expanded beam is directly sent to the inspected surface, and the resulting interference pattern is imaged such that it can either be directly observed through an eyepiece (ocular lens) or registered with a monochrome electronic image sensor.

The inspected surface can be that of a mirror or some other kind of optical element; for use as an end mirror, one just requires some significant reflectivity of the surface, and there should be no additional reflection which could spoil the interference pattern. Some elements (e.g. lenses, prisms and mirror substrates) can also be inserted in the beam path for inspection in transmission, i.e., they are combined with a suitable kind of mirror.

For inspecting aspheric optics, one will usually require a high-quality reference surface (made e.g. from an optical flat) with which further devices can be inspected, because the deviation from a spherical mirror, for example, may be too high to measure.

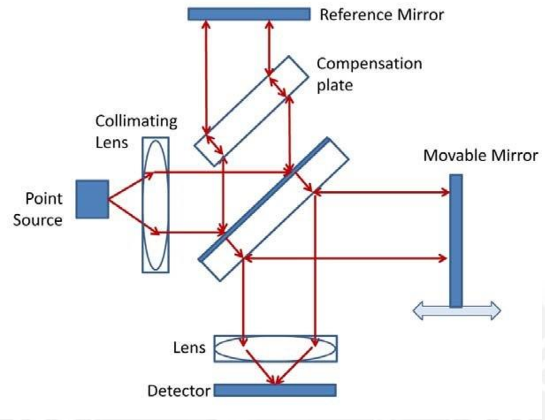

Fig. 3.25 Twyman–Green Interferometer

[source: https://www.researchgate.net/figure/Schematic-of-the-Twyman-Green-Interferometer-Based-on-Born-and-Wolf-1999_fig4_44788333]

The inspected surface must be imaged to the detector, such that each point in the image corresponds to a point on the inspected surface.

The object under test or the reference mirror is intentionally very slightly tilted e.g. by turning a micrometer screw, so that one obtains an interference pattern with regular stripes having an appropriate spacing. These stripes are perfect lines if the test surface exactly matches the reference surface. Any deviations between the surface shapes lead to distortions of those stripes (Fizeau curves). For topographic deviations of several wavelengths, one may simply count the number of stripes in order to measure the height.

Recorded digital images may be more closely analyzed with suitable computer software, which may allow detailed measurements of surface shape deviations.

The used reference mirror as well as the beam splitter and other optical components should have a very high optical quality, so that any observed distortions are only due to imperfections of the investigated objects.

3.4 Machine Tool Measurement Using Laser Interferometer

When the machine tool is idle and unloaded, tests performed are called as alignment tests.

Alignment test is carried out 'to check grade of manufacturing accuracy of the machine tool'. It consists of checking the relation between various machine parts or elements (such as bed, table, spindle etc.)

3.4.1 Alignment Testing on Machine Tools and its importance

The accurate production of the component parts depends on the accuracy of the machine tools. The quality of workpiece depends on the following factors:

- Rigidity and stiffness of machine tool and its components.
- Alignment of various components in relation to one another,
- Quality and accuracy of the control devices and the driving mechanism.

Precise alignment of machine tool components has the following advantages:

- It produces high quality machined components.
- It reduces power consumption of machinery.
- It increases machine reliability and productivity.
- It reduces machine repair costs.
- It minimizes the machine installation and repair time.
- It reduces machine down time and increases machine availability.
- It decreases wear on bearings, seals, shafts and couplings.
- It reduces vibrations in machine tools.
- It significantly reduces the damage to machine tool components.

Various types of alignment tests conducted on machine tools are as follows

a) Straightness
b) Flatness
c) Parallelism, Equidistance and Coincidence
    i. Parallelism of Lines and Planes
    ii. Parallel Motion

d) Squareness of straight lines and planes
e) Rotation
    i. Concentricity or out of round
    ii. Eccentricity
    iii. Out of true running
    iv. Periodical axial slip
    v. Radial throw of an axis at a given point
f) Movement of all working components

In general, the following alignment test for applied to any Machine tools

- Test for levelling the installation of a machine tool in horizontal and vertical plane
- Test for perpendicularity of guideways to other guideways
- Test for flatness of machine bed straightness and parallelism of bed ways on the bearing surface
- Test for true running of the main spindle and its Axis movements
- Test for a line of moment of various members such as spindle tables and cross slides
- Test for parallelism of spindle axis to guideways for the bearing surfaces

Laser as means of alignment checking

Laser alignment checking can be used for the following purposes

- To Align horizontal boring Mills, Vertical boring Mills, vertical machining centres, vertical turret lathe, gantries, surface grinder, injection moulding machines, presses, high Precision laser and water Jet cutting machines.
- To verify and correct roll parallelism in paper mills, printing presses, film line and blown film lines
- To measure and align the flatness of almost any surface (square, frames, ways, flanges, circles Etc.).
- To ensure the squareness up to three surfaces
- To ensure the straightness of horizontal and vertical surfaces
- To ensure the parallelism of horizontal and vertical surfaces

- for other applications such as checking the plumpness of a vertical surface Checking way twist and parallelism between horizontal surfaces and checking way twist and parallelism between vertical surfaces

Laser systems can be used to measure a great number of geometric and dynamic properties of a machine tool. Following measurements can be performed using laser interferometer

a. linear positioning accuracy and repeatability of Axis
b. straightness of Axis
c. squareness between Axis
d. flatness of surface
e. levelness of the plane surface
f. parallelism between surface
g. testing accuracy of rotary axis

3.4.2 Straightness testing using laser interferometer

Straightness error is one of the fundamental geometric tolerances that must be strictly controlled for precision guideways or stages. Several methods used for straightness measurements are: laser interferometer with straightness optics, a straight edge with displacement sensors such as linear variable displacement transducer and gap sensor, and incremental angular measurements using autocollimator or angular measurement optics, etc. Among these methods, the laser interferometer has been widely adopted to obtain high precision straightness measurement.

Some commercial instruments have been successfully developed, such as the Agilent 5529A interferometer and the Renishaw ML10 interferometer a common disadvantage in these instruments is that they cannot provide information about the relative position of the measured straightness errors Therefore in practice it is inconvenience to repair the guideways or to adjust the stages because the users do not know the exact position of the straightness error. a new interferometer design based on heterodyne interferometry for measuring straightness and its position is proposed, which can overcome the disadvantage described above. The theory and optical configuration of this new interferometer are developed and subjected to experimental testing with a linear stage to verify the feasibility of the interferometer as well as a flexure-hinge stage to demonstrate the interferometer's capability of nanometer measurement accuracy.

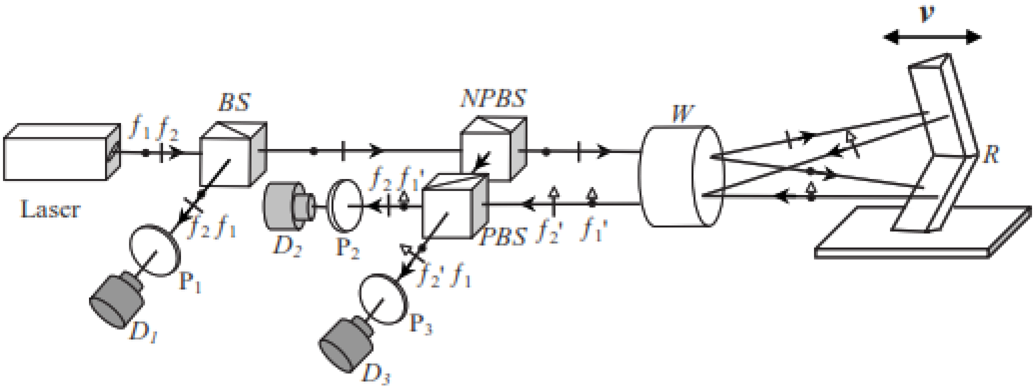

Fig. 3.26 schematic diagram of the laser interferometer for measuring straightness and its position based on heterodyne interferometry.

[source: https://www.researchgate.net/figure/Schematic-of-the-Twyman-Green-Interferometer-Based-on-Born-and-Wolf-1999_fig4_44788333]

A stabilized laser as light source emits a orthogonally linearly polarized laser beam with dual frequencies (f_1 and f_2). The laser beam is divided by a beam- splitter (BS) into two beams. One beam, as the reference beam, passes through the first polarizer (P1) and projects on to the first photodetector (D1), and then a reference signal is produced. Another beam, as the measurement beam, is divided by a nonpolarizing BS into a reflected beam (RB) and a transmitted beam (TB). The RB incidents onto a polarizing BS (PBS). The TB passes through a Wollaston prism (W) and is split into two divergent beams containing f_1 and f_2 separately. The two divergent beams are then incident onto a retroreflector (R) which is composed of two right-angle prisms.

The R is placed on the measured object which straightness is required to be tested. The R reflects the two divergent beams, whose frequencies become f1±f1 and f2±f2 caused by the Doppler effect, back into the W where they are recombined into one beam at another point of the W. After passing through the W, the combined beam incidents onto the PBS. Then, (a) the beam with frequency of f1 ±f1 transmitting through the PBS and the beam f2 of the RB reflected by the PBS recombine into one beam (BI). The BI passes through the second polarizer (P2) and projects onto the second photodetector (D2). So, the first measurement signal is produced. (b) The beam with frequency of f2 $\pm \Delta$f2 reflected by the PBS and the beam f1 of the RB transmitting through the PBS recombine into another one beam (BII). The BII passes through the third polarizer (P3) and projects onto the third photodetector (D3). So, the second measurement signal is produced.

Use of Laser for Alignment Testing

The alignment tests can be carried out over greater distances and to a greater degree of accuracy using laser equipment.

- Laser equipment produces real straight line, whereas an alignment telescope provides an imaginary line that cannot be seen in space.
- This is important when it is necessary to check number of components to a predetermined straight line. Particularly if they are spaced relatively long distances apart, as in aircraft production and in shipbuilding.
- Laser equipment can also be used for checking flatness of machined surface by direct displacement. By using are optical square in conjunction with laser equipment squareness can be checked with reference to the laser base line.

3.4.3 ALIGNMENT TESTS ON MILLING MACHINE

3.4.3.1. Cutter Spindle Axial Slip or Float:

Axial slip is defined as, "an axial movement of spindle, which may repeat positively with each revolution". Clamp the dial gauge stand to table, such that, the plunger or feeler of dial gauge indicator is touching the face of locating spindle shoulder.

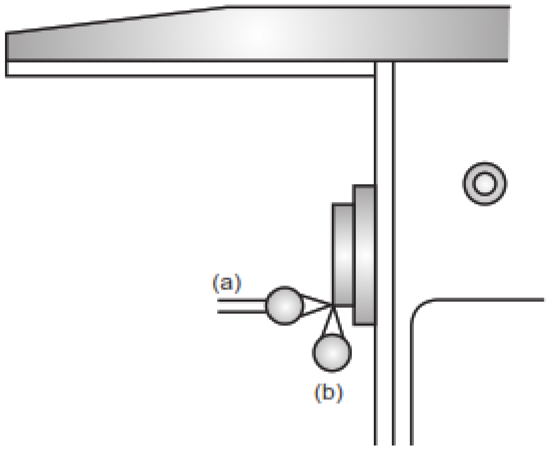

Fig. 3.27 Cutter Spindle Axial Slip or Float

[source: Metrology And Quality Control by Vinod Thombre Patil, Pg. No 8.20]

- Now rotate the spindle about its centre and note down the variations observed in the readings shown on dial gauge indicator.
- This is to be tested at two points 180° apart from each other. It is expected that, the value of maximum variation in dial gauge readings should not be more than specified permissible range.

3.4.3.2. Transverse Movement Parallelism with Spindle Axis:

- Fig. shows the arrangement required to carry out test, using a dial gauge indicator along with its mounting stand arrangement.

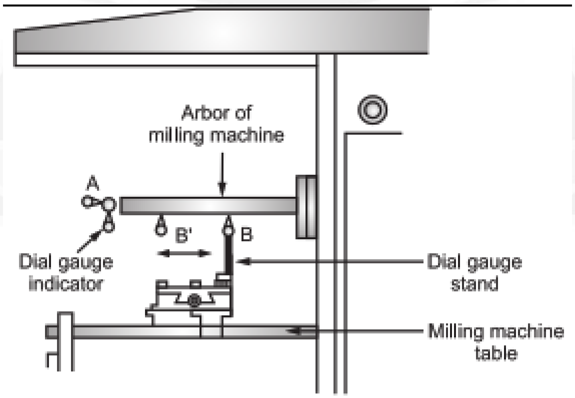

Fig. 3.28 Transverse Movement Parallelism with Spindle Axis

[source: Metrology And Quality Control by Vinod Thombre Patil, Pg. No 8.21]

- Mount and fix the dial gauge indicator with the help of its stand, on the table of milling machine.

- Use Arbor of milling machine as shown in Fig. A stationery mandrel can also be used instead of Arbor.
- Initially, place the plunger (or feeler) of dial gauge indicator touching the Arbor at point 'B' to check along vertical plane. Note down the reading of dial gauge indicator (1st reading).
- Now move the dial gauge indicator along with its stand in transverse direction up to point B' and note down the second reading of dial gauge indicator (2nd reading).
- If no variation is found in first (1st) and second (2nd) reading, then transverse movement is parallel with spindle axis.

3.4.3.3. True Running of Internal Taper:

• Fix a mandrel as shown in Fig.

•Dial gauge indicator is mounted with the help of dial gauge stand, in such a way that, plunger will touch the surface of mandrel.

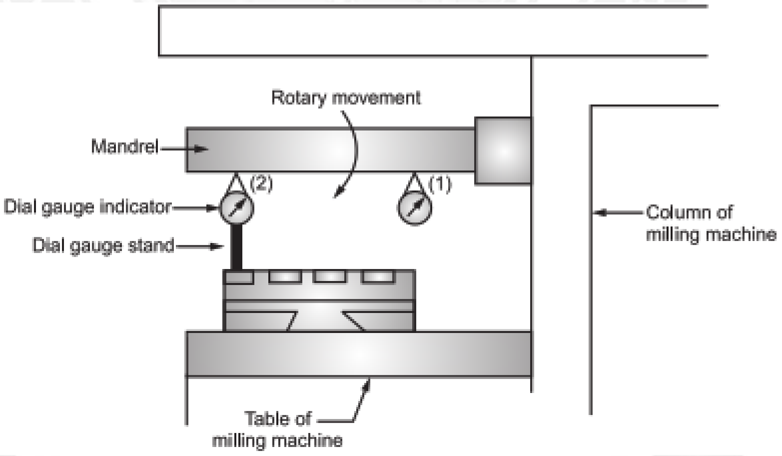

Fig. 3.29 Transverse Movement Parallelism with Spindle Axis

[source: Metrology And Quality Control by Vinod Thombre Patil, Pg. No 8.21]

- It is ensured that, plunger remains in contact with mandrel, while carrying the test.
- This test is carried out at two places, given below:

(i) Near to spindle nose, refer position (1).

(ii) At a distance of 300 mm from spindle nose, refer position (2).

- Consider that plunger of dial gauge indicator is at position (1). Now, rotate the mandrel and observe the readings shown on dial indicator, to find out the value of maximum variation (if present) is noted down as 1st reading.
- Now, dial gauge indicator is mounted with the help of its stand at position (2), which is 300 mm away from position (1). Repeat the same procedure and note down 2nd reading.
- Difference between 1st and 2nd readings indicates an error in true running of internal taper.
- This error should not exceed the specified permissible value.

3.4.3.4. Surface Parallelism with Longitudinal Movement:

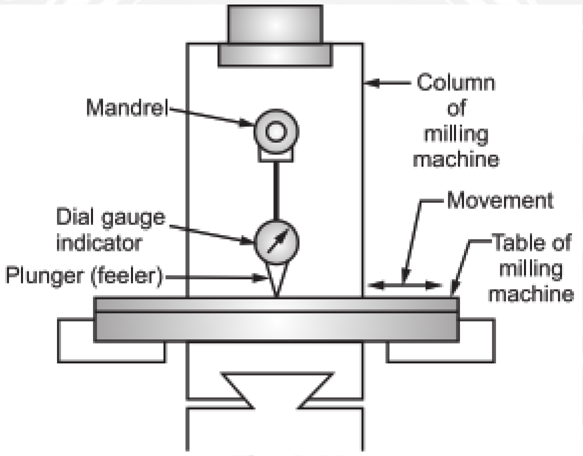

Fig. 3.30 Transverse Movement Parallelism with Spindle Axis

[source: Metrology And Quality Control by Vinod Thombre Patil, Pg. No 8.22]

- Fix a mandrel and a dial gauge indicator in such a way that, the plunger of dial gauge indicator will touch the table surface. Also, plunger is slightly pressed against the table surface, so that, it will be always in contact with table surface throughout the test. Refer Fig.
- Test the table surface for maximum travel.
- Readings shown by dial gauge indicator are observed to find out maximum variation, i.e., error in parallelism of surface during horizontal movement. This error should not exceed more than the specified permissible value.

3.5 CO-ORDINATE MEASUREMENT MACHINES (CMM)

The term measuring machine generally refers to a single-axis measuring instrument. Such an instrument is capable of measuring one linear dimension at a time. The term coordinate measuring machine refers to the instrument/machine that is capable of measuring in all three orthogonal axes. Such a machine is popularly abbreviated as CMM.

A CMM enables the location of point coordinates in a three-dimensional (3D) space. It simultaneously captures both dimensions and orthogonal relationships. Another remarkable feature of a CMM is its integration with a computer. The computer 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.

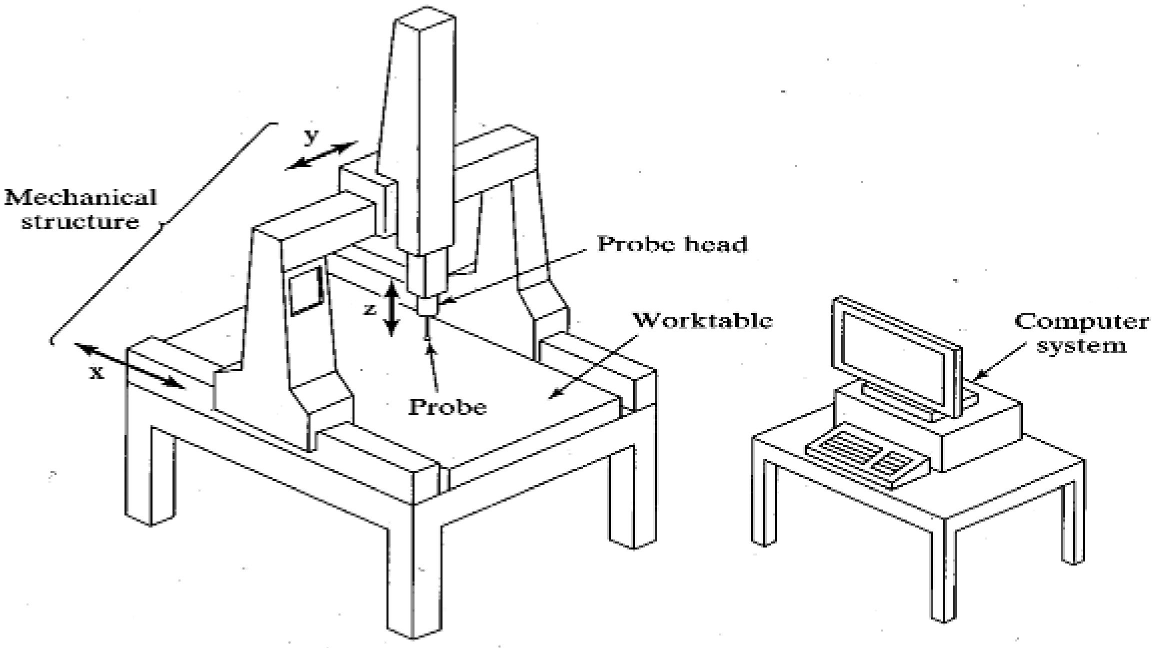

Fig. 3.31 CO-ORDINATE MEASUREMENT MACHINE

[source: https://www.slideshare.net/dharanimech/cmm-3?from_action=save]

The first batch of CMM prototypes appeared in the United States in the early 1960s. However, the modern version of CMM began appearing in the 1980s, thanks to the rapid developments in computer technology. The primary application of CMM is for inspection. Since its functions are driven by an on-board computer, it can easily be integrated into a computer-integrated manufacturing (CIM) environment. Its potential as a sophisticated measuring machine can be exploited under the following conditions:

Multiple features The more the number of features (both dimensional and geometric) that are to 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.

3.5.1 Introduction

- Coordinate metrology is concerned with the measurement of the actual shape and dimensions of an object and comparing these with the desired shape and dimensions.
- In this connection, coordinate metrology consists of the evaluation of the location, orientation, dimensions, and geometry of the part or object.
- A Coordinate Measuring Machine (CMM) is an electromechanical system designed to perform coordinate metrology.

3.5.2 Types of Measuring Machines

- Length bar measuring machine.
- Newell measuring machine.
- Universal measuring machine.
- Co-ordinate measuring machine.
- Computer controlled co-ordinate measuring machine.

3.5.3 Structure

The basic version of a CMM has three axes, along three mutually perpendicular directions. Thus, the work volume is cuboidal. 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 illustrates the five basic configuration types: cantilever, bridge, column, horizontal arm and gantry.

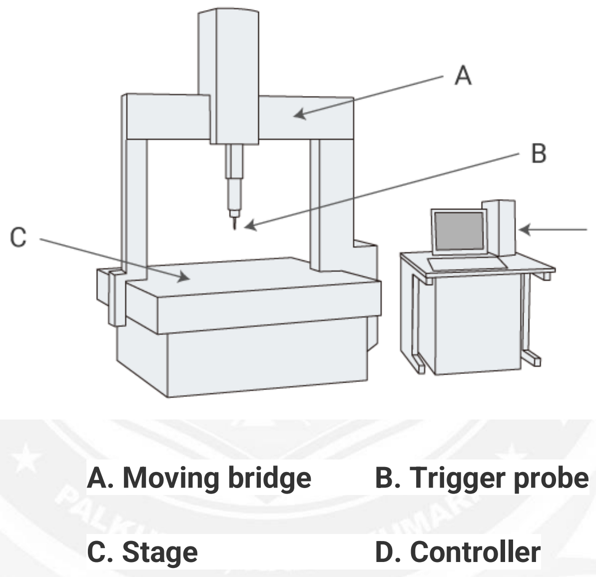

Fig. 3.32 Co-Ordinate Measurement Machines (CMM)

[source: https://www.keyence.com/ss/products/measure-sys/measurement-selection/type/3d.jsp]

3.5.4 TYPES OF CO-ORDINATE MEASUREMENT MACHINES (CMM)

3.5.4.1 Cantilever type CMM

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.

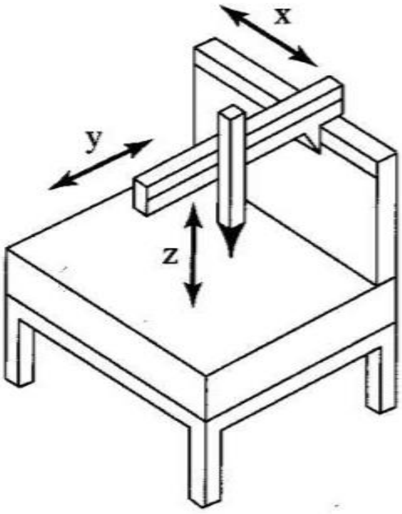

Fig. 3.33 Cantilever type CMM

[source: https://www.slideshare.net/dharanimech/cmm-3?from_action=save]

3.5.4.2 Bridge type CMM

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.

a) Moving Bridge type CMM

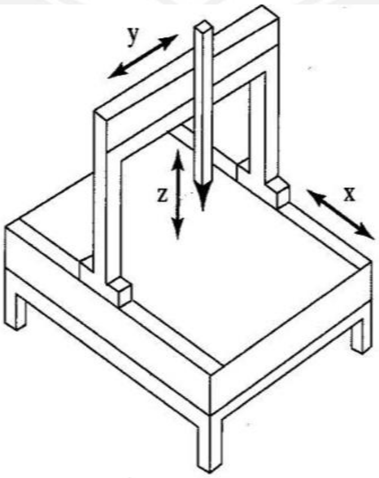

Fig. 3.33 Moving Bridge type CMM

[source: https://www.slideshare.net/dharanimech/cmm-3?from_action=save]

- Most widely used
- Has stationary table to support work piece to be measured and a moving bridge
- **Disadvantage-** with this design, the phenomenon of yawing (sometimes called walking) can occur- affect the accuracy
- **Advantage-** reduce bending effect

b) Fixed Bridge type CMM

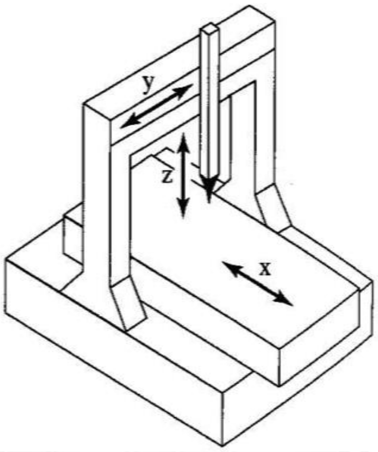

Fig. 3.34 Fixed Bridge type CMM

[source: https://www.slideshare.net/dharanimech/cmm-3?from_action=save]

- In the fixed bridge configuration, the bridge is rigidly attached to the machine bed
- This design eliminates the phenomenon of walking and provides high rigidity

3.5.4.3 Column type CMM

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.

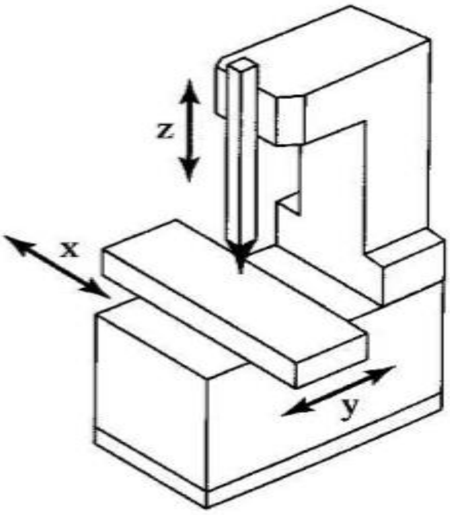

Fig. 3.35 Column type CMM

[source: https://www.slideshare.net/dharanimech/cmm-3?from_action=save]

3.5.4.4 Horizontal arm type CMM

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.

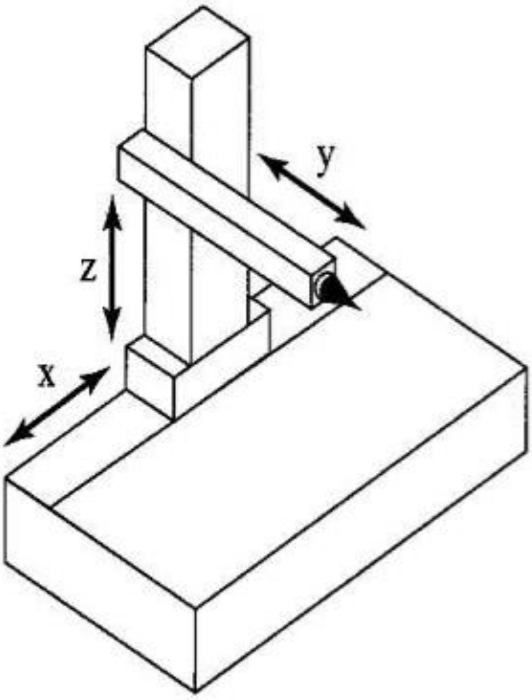

Fig. 3.36 Horizontal arm type CMM

[source: https://www.slideshare.net/dharanimech/cmm-3?from_action=save]

3.5.4.5 Gantry type CMM

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. Some of the machines may have rotary tables or probe spindles, which will enhance the versatility of the machines. The work space that is bounded by the limits of travel in all the axes is known as the work envelop. Laser interferometers are provided for each of the axes if a very precise measurement is necessary.

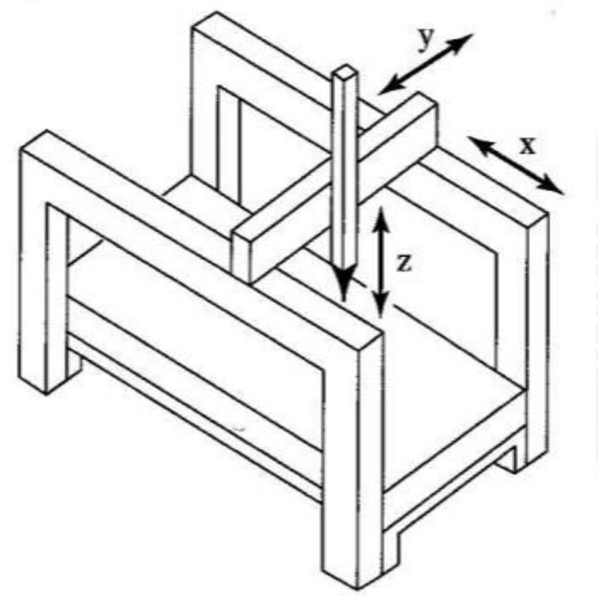

Fig. 3.37 Gantry type CMM

[source: https://www.slideshare.net/AUSTINMOSES/probing-systems-seminar?from_action=save]

3.5.5 Modes of Operation

Modes of operation are quite varied in terms of type of construction and degree of automation. Accordingly, 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, a 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.

3.5.6 CMM Operation and Programming

Positioning the probe relative to the part can be accomplished in several ways, ranging from manual operation to direct computer control.

Computer-controlled CMMs operate much like CNC machine tools, and these machines must be programmed.

3.5.6.1 CMM Operation

This section explains the operation or the measurement process using a CMM. Most modern CMMs invariably 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. A 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 recur 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.

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.

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. 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, 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

3.5.7 CMM Controls

The methods of operating and controlling a CMM can be classified into four main categories:

1. Manual drive,
2. Manual drive with computer-assisted data processing,
3. Motor drive with computer-assisted data processing, and
4. Direct Computer Control with computer-assisted data processing

1. In **Manual drive CMM**, the human operator physically moves the probe along the machine's axes to make contact with the part and record the measurements.

- The measurements are provided by a digital readout, which the operator can record either manually or with paper print out.
- Any calculations on the data must be made by the operator.

2. A CMM with **Manual drive and computer-assisted data processing** provides some data processing and computational capability for performing the calculations required to evaluate a give part feature.

- The types of data processing and computations range from simple conversions between units to more complicated geometry calculations, such as determining the angle between two planes.

3. A **Motor-driven CMM with computer-assisted data processing** uses electric motors to drive the probe along the machine axes under operator control.

- A joystick or similar device is used as the means of controlling the motion.
- Motor-driven CMMs are generally equipped with data processing to accomplish the geometric computations required in feature assessment.

4. A CMM with **Direct computer control** (DCC) operates like a CNC machine tool. It is motorized and the movements of the coordinate axes are controlled by a dedicated computer under program control.

- The computer also performs the various data processing and calculation functions.
- As with a CNC machine tool, the DCC CMM requires part programming.

3.5.8 DCC CMM Programming

There are two principle methods of programming a DCC measuring machine:

1. Manual lead through method.

2. Off-line programming.

1. In the **Manual Lead through method**, the operator leads the CMM probe through the various motions required in the inspection sequence, indicating the points and surfaces that are to be measured and recording these into the control memory.

- During regular operation, the CMM controller plays back the program to execute the inspection procedure.

2. **Off-line Programming** is accomplished in the manner of computer-assisted NC part programming; The program is prepared off-line based on the part drawing and then downloaded to the CMM controller for execution.

3.6 PROBES IN CMM

A **Coordinate Measuring Machine** is defined by the ability of its probe. As with CMMs, there are several types of probes available. There is the contact probe, which measures the workpieces by making contact with them. The non-contact probe that employs lasers or machine vision probes which scan with optical sensors.

Contact probes are a more accurate way of measuring. However, the laser or machine vision probes are far quicker to use, while still holding a high degree of accuracy. There are also multi-sensor probes which combine both touch and optical scanning, giving the benefit of both types in one probe.

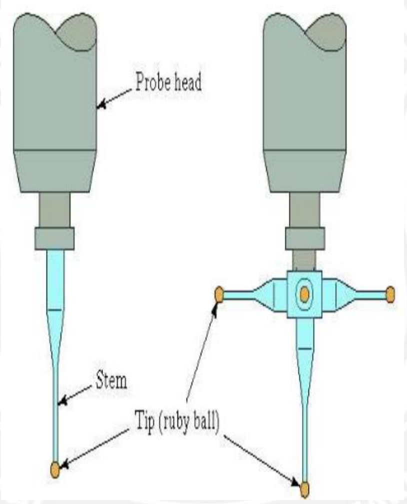

Fig. 3.38 PROBES IN CMM

[source: https://www.slideshare.net/dharanimech/cmm-3?from_action=save]

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.

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 mitigates 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. However, 'touch trigger' probes, which use differences in contact resistance to indicate deflection of the probe, are also popular.

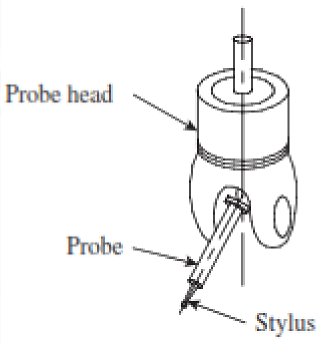

Fig. 3.39 Probe Assembly

[source: "Engineering Metrology & Measurements", N.V. Raghavendra., page-235]

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.

3.6.1 TYPES OF PROBES

3.6.1.1 Contact Probes

The two most common contact probes are Touch Trigger Probes and Analog Scanning Probes.

a. Touch Trigger Probes:

A touch trigger probe has a stylus that is attached to a bearing plate. This is then connected to pressure sensors inside the housing of the probe. Each time the probe makes contact with the workpiece, it generates an electrical signal. The signal is sent back to the CMM to create accurate measurements.

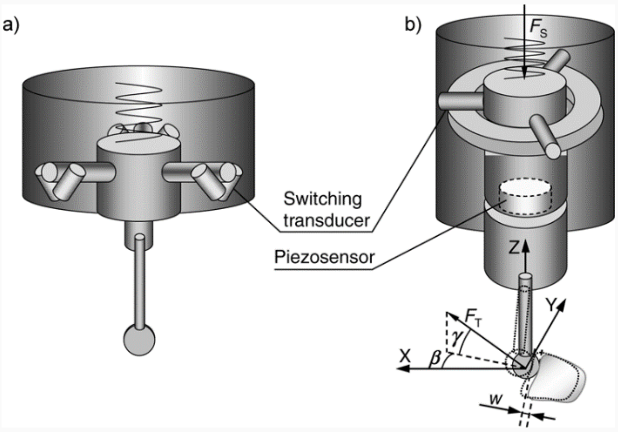

Fig. 3.40 Schematic of the touch trigger probes. (a) One-stage type with an electromechanical switching transducer. (b) two-stage type based on a piezoelectric transducer.

[source: https://www.researchgate.net/figure/Schematic-of-the-touch-trigger-probes-a-One-stage-type-with-an-electromechanical_fig1_220410845]

With a touch trigger probe, the head is mounted at the end of one of the CMM's moving axes. The probe can be rotated either manually or automatically and can accommodate a variety of attachments and stylus tips.

The advantage of touch probes is that they are versatile and flexible. By incorporating the piezo-based sensors, the effect of stylus bending was eliminated, while the strain gauge technology advancements have ensured that the probes trigger with constant force regardless off the angle of contact it has with the workpiece. These two things combined eliminate directional sensitivity which has given these probes a sub-micron level of accuracy.

b. Analog Scanning Probes

Analogue scanning probes are another type of stylus-based probes that are used for measuring contoured surfaces such as sheet metal assemblies. Unlike digital probes, which touch individual points, the analogue probe keeps continual contact with the workpiece taking measurements as it is dragged across it.

Fig. 3.41 Analog Scanning Probes

[source: https://slideplayer.com/slide/13175950/]

The continual contact which yields analogue measurements offers dramatically increased levels of data acquisition. The structure of the continuous analogue scanning (CAS) probes is based on continuous data acquisition rather than the point to point of a digital probe.

Analogue scanning probes are extremely useful for collecting the measurement data for complex contoured shapes such as turbine engine blades, cams, automobile bodies, crankshafts and prosthetics.

There are two types of continuous analogue scanning, CAS, systems:

1. **Closed-Loop Systems:** This probe automatically detects changes in the surface and direction of the workpiece and adjusts itself accordingly to ensure that it maintains contact at all times. The closed-loop system is particularly useful for digitising unknown and complex shapes.

2. **Open-Loop Systems:** This probe gets driven along a specific path using dimensional information obtained from a data file. The open-loop system is particularly useful for high-speed data gathering on parts with geometry that has been well defined by surface points and vectors or by CAD data.

Analogue probes can acquire up to fifty times more data than touch trigger probes in the same amount of time. The more data that is collected, the more confidence in its accuracy. If there are large gaps between data points the accuracy of the data may not be so assured.

Another advantage of analogue scanning probes over digital probes is their ability to also be used as a touch trigger probe which gives its users more flexibility. An operator will be able to choose which features require a quick touch and which need more time devoted to them. A critical feature that is particularly complex would require continual contact.

3.6.1.2 Non-Contact Probes

A non-contact probe is essential for any workpiece that is likely to become deformed under the pressure of a contact probe. They are also useful for more complex, smaller and high-precision workpieces. A non-contact probe is either laser-based or vision-based.

a. Laser Probes

A laser probe works in a similar way to the touch trigger probe. Instead of using a stylus, it uses a concentrated beam of light to take readings. The beam of light acts as an optical switch. When the beam is projected onto the part, the position will then be read by triangulation through a lens inside the probe receptor.

Fig. 3.42 Analog Scanning Probes

[source: https://www.sariki.es/en/measuring-equipment/3d-measurement/multisensor-probes/laser-scanner-probe/]

This technique is similar to the one used by surveyors when they want to find a position or location with bearings from a known distance between two fixed points.

b. Vision-Based Probes

Microprocessors and other very small parts require the use of vision-based probes. Rather than measuring the parts themselves, a mould is electronically digitised that will generate accurate dimensions for future workpieces.

Fig. 3.43 Vision-Based Probes

[source: https://www.renishaw.com/en/revo-2-rvp-vision-probe--35452]

The Vision-Based Probes is a high-definition camera that is capable of generating multiple measurement points in one frame. This allows the features to be measured and compared to the electronic model by counting the pixels. A vision system lens only requires calibration once which is a huge advantage as other probes require recalibration more often.

The key advantage of a non-contact probe is that it enables the user to collect data from a larger surface area in less time than is possible with contact probes. However, the downside is that the accuracy of the readings is not as great as the contact probes. If you want speed over accuracy, then a non-contact probe is ideal. If you have a particularly complex essential part, you would be better suited to using a contact probe.

3.6.2 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 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.

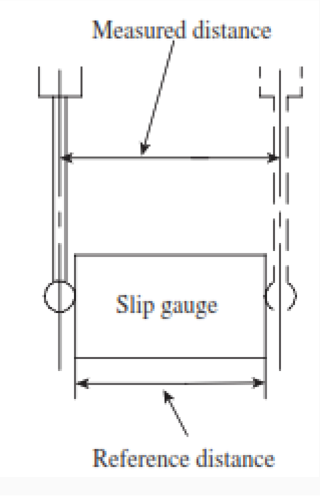

Fig. 3.44 Probe Calibration

[source: “Engineering Metrology & Measurements”, N.V. Raghavendra., page-237]

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.

3.6.3 Major Applications

The CMM is a 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 workpiece is inspected. A further extension of this principle may include computer assisted design and drafting (CADD).

3. Another major use (or abuse?) 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.

3.6.4 ADVANTAGES

- The inspection rate is increased.

- Accuracy is more.
- Operator’s error can be minimized.
- Skill requirements of the operator is reduced.
- Reduced inspection fix Turing and maintenance cost.
- Reduction in calculating and recording time.
- Reduction in set up time.
- No need of separate go / no go gauges for each feature.
- Reduction of scrap and good part rejection.
- Reduction in off line analysis time.

3.6.5 DISADVANTAGES

- The table and probe may not be in perfect alignment.
- The probe may have run out.
- The probe moving in Z-axis may have some perpendicular errors.
- Probe while moving in X and Y direction may not be square to each other.
- There may be errors in digital system.

3.6.6 CAUSES OF ERRORS IN CMM

The table and probes are in imperfect alignment. The probes may have a degree of run out and move up and down in the Z-axis may occur perpendicularity errors. So CMM should be calibrated with master plates before using the machine.

Dimensional errors of a CMM is influenced by

- Straightness and perpendicularity of the guide ways.
- Scale division and adjustment.
- Probe length.
- Probe system calibration, repeatability, zero-point setting and reversal error.
- Error due to digitization.
- Environment

- Other errors can be controlled by the manufacture and minimized by the measuring software. The length of the probe should be minimum to reduce deflection.
- The weight of the work piece may change the geometry of the guide ways and therefore, the work piece must not exceed maximum weight.
- Variation in temperature of CMM, specimen and measuring lab influence the uncertainly of measurements.
- Translation errors occur from error in the scale division and error in straightness perpendicular to the corresponding axis direction.
- Perpendicularity error occurs if three axes are not orthogonal.

3.6.7 Comparison between conventional and coordinate measuring technology

TABLE 3.1 Comparison between conventional and coordinate measuring technology

CONVENTIONAL METROLOGY	COORDINATE METROLOGY
Manual, time consuming alignment of the test piece	Alignment of the test piece not necessary
Single purpose and multi-point measuring instruments making it hard to adapt to changing measuring task	Simple adaptation to the measuring test by software
Comparison of measurement with material measures, i.e., gauge block	Comparison of measurement with mathematical or numerical value
Separate determination of size, form, location and orientation with different machines	Determination of size, form, location and orientation in one setup using one reference system

3.6.8 Features of CMM Software

- **Measurement of diameter, center distance, length.**
- **Measurement of plane and spatial carvers.**
- **Minimum CNC programmed.**
- **Data communications.**
- **Digital input and output command.**
- **Program me for the measurement of spur, helical, bevel' and hypoid gears.**
- **Interface to CAD software**
- **Generally, software packages contain some or all of the following capabilities:**

1. **Resolution selection**
2. **Conversion between SI and English (mm and inch)**
3. **Conversion of rectangular coordinates to polar coordinates**
4. **Axis scaling**
5. **Datum selection and reset**
6. **Circle center and diameter solution**
7. **Bolt-circle center and diameter**
8. **Save and recall previous datum**
9. **Nominal and tolerance entry**
10. **Out-of tolerance computation**

3.7 BASIC CONCEPTS OF MACHINE VISION SYSTEM

Machine vision can be defined as a means of simulating the image recognition and analysis capabilities of the human system with electronic and electromechanical techniques.

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. 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.

3.7.1 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, illustrated in Fig., involves the following four important stages:

1. Image generation and digitization

2. Image processing and analysis

3. Image interpretation

4. Generation of actuation signals

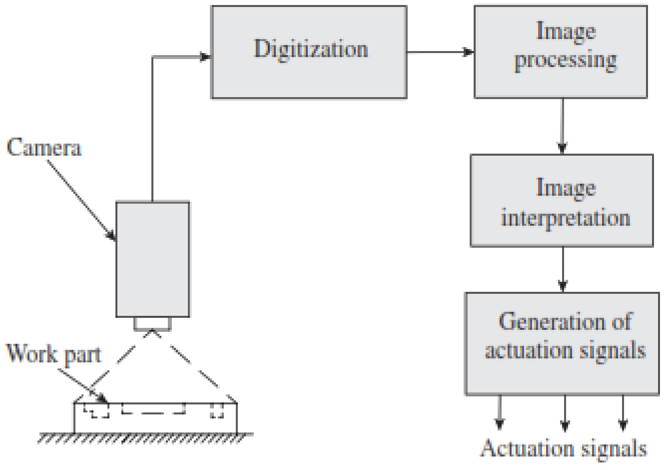

Fig. 3.46 Stages of Machine Vision

[source: "Engineering Metrology & Measurements", N.V. Raghavendra., page-254]

3.7.1.1 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).

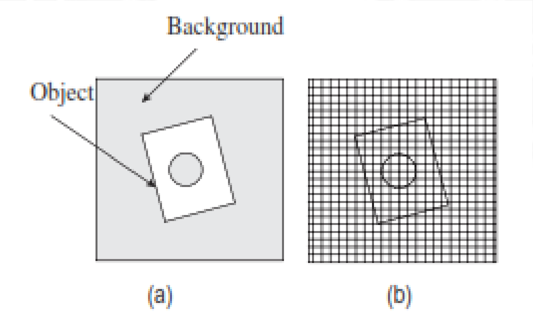

Fig. 3.47 Vision system (a) Object and background (b) Matrix of pixels

[source: “Engineering Metrology & Measurements”, N.V. Raghavendra., page-254]

This digitized frame of the image is referred to as the frame buffer. While Fig. 10.41(a) illustrates the object kept in the scene of vision against a background, Fig. 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. Two types of cameras are used in machine vision applications, namely vidicon cameras and solid-state cameras. Vidicon cameras are analog cameras, quite similar to the ones used in conventional television pictures.

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.

3.7.1.2 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.

3.7.1.3 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.

3.7.1.4 Generation of Actuation Signals

Once the object is identified, the vision system should direct the inspection station to carry out the necessary action. In a flexible inspection environment, the work-cell controller should generate the actuation signals to the transfer machine to transfer the work part from machining stations to the inspection station and vice versa. Clamping, declamping, gripping, etc., of the work parts are done through actuation signals generated by the work-cell controller.

3.7.2 Vision System

The schematic diagram of a typical vision system is shown. This system involves image acquisition; image processing Acquisition requires appropriate lighting. The camera and store digital image processing involve manipulating the digital image to simplify and reduce number of data points. Measurements can be carried out at any angle along the three reference axes x y and z without contacting the part. The measured values are then compared with the specified tolerance which stores in the memory of the computer.

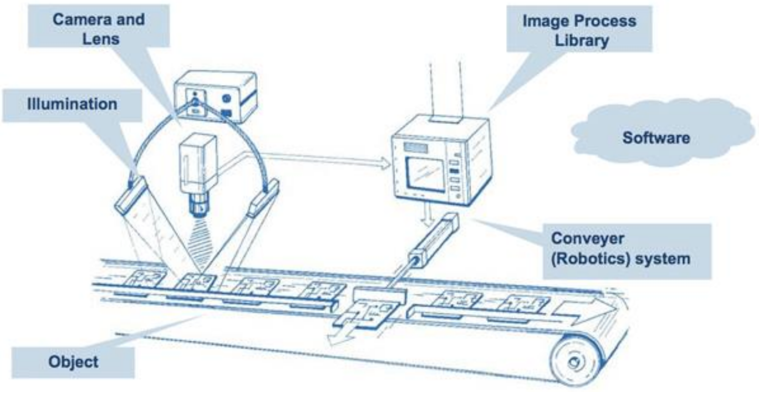

Fig. 3.47 Machine Vision System

[source: https://www.roboticstomorrow.com/article/2019/12/what-is-machine-vision/14548]

The main advantage of vision system is reduction of tooling and fixture costs, elimination of need for precise part location for handling robots and integrated automation of dimensional verification and defect detection.

3.7.3 Principle

Four types (OR) Elements of machine vision system and the schematic arrangement is

Shown

(i) Image formation.
(ii) Processing of image in a form suitable for analysis by computer.
(iii) Defining and analyzing the characteristic of image.
(iv) Interpretation of image and decision-making.

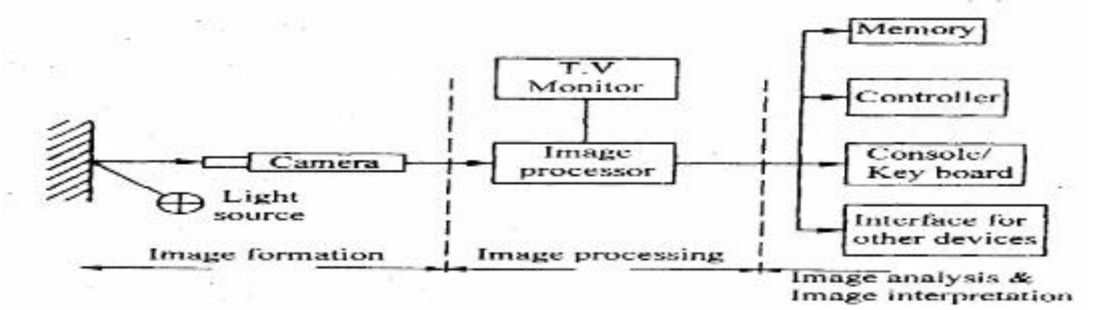

Fig. 3.48 Principle Machine Vision System

[source: https://what-when-how.com/metrology/principle-of-working-metrology/]

(i) **Image formation.**

For formation of image suitable light source is required. It may consist of incandescent light, fluorescent tube, fiber-optic bundle, arc lamp, or strobe light. Laser beam is used for triangulation system for measuring distance. Polarised or ultraviolet light is used to reduce glare or increase contrast. It is important that light source is placed correctly since it influences the contrast of the image. Selection of proper illumination technique, (viz., back lighting, front lighting-diffused or directed bright field, or directed dark field, or polarised, structured light) is important. Back lighting is suited when a simple silhouette image is required to obtain maximum image contrast.

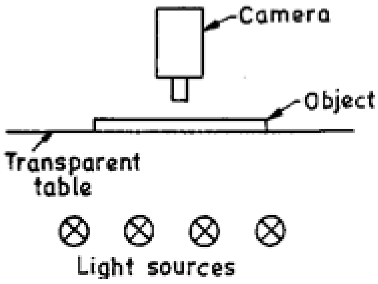

Fig. 3.49 Back lighting.

[source: https://what-when-how.com/metrology/principle-of-working-metrology/]

Front lighting is used when certain key features on the surface of the object are to be inspected. If a three-dimensional feature is being inspected, side lighting or structured lighting may be required. The proper orientation and fixturing of part also deserve full attention. An image sensor like vidicon camera, CCD or CID camera is used to generate the electronic signal representing the image. The image sensor collects light from the scene through a lens and using a photosensitive target, converts it into electronic signal. Most image sensors generate signals representing two-dimensional arrays (scans of the entire image).

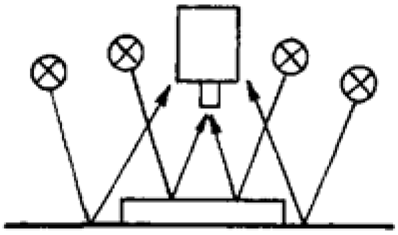

Fig. 3.50 Diffused front lighting.

[source: https://what-when-how.com/metrology/principle-of-working-metrology/]

Vidicon Camera used in closed-circuit television systems can be used for machine vision systems. In it, an image is formed by focussing the incoming light through a series of lenses onto the photoconductive face plate of the vidicon tube. An electron beam within the tube scans the photo conductive surface and produces an analog output voltage proportional to the variations in light intensity for each scan line of the original scene. It provides a great deal of information of a scene at very fast speeds. However, they tend to distort the image due to their construction and are subject to image burn-in on the photo conductive surface. These are also susceptible to damage by shock and vibration.

Solid State Cameras.

These are commonly used in machine vision systems. These employ charge coupled device (CCD) or charge injected device (CID) image sensors. They contain matrix or linear array of small, accurately spaced photo sensitive elements fabricated on silicon chips using integrated circuit technology. Each detector converts the light falling on it, through the camera lens, into analog electrical signal corresponding to light intensity. The entire image is thus broken down into an array of individual picture elements (pixels).

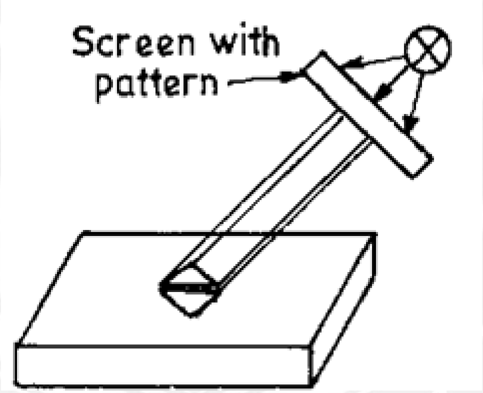

Fig. 3.51 Structured light.

[source: https://what-when-how.com/metrology/principle-of-working-metrology/]

Typical matrix array solid state cameras may have 256 x 256 detector elements per array. Solid-state cameras are smaller, rugged and their sensors do not wear out with use. They exhibit less image distortion because of accurate placement of the photodetectors. CCD and CID differ primarily in how the voltages are extracted from the sensors.

(ii) Image Processing. The series of voltage levels available on detectors representing light intensities over the area of the image need processing for presentation to the microcomputer in a format suitable for analysis. A camera may typically form an image 30 times per sec i.e. at 33 m sec intervals. At each time interval the entire image has to be captured and frozen for processing by an image processor. An analog to digital converter is used to convert analog voltage of each detector into digital value.

If voltage level for each pixel is given either 0 or 1 value depending on some threshold value, it is called Binary System. On the other hand gray scale system assigns upto 256 different values depending on intensity to each pixel. Thus in addition to black and white, many different shades of gray can be distinguished. This thus permits comparison of objects on the basis of surface characteristics like texture, colour, orientation, etc., all of which produce subtle variations in light intensity distributions. Gray scale systems are used in applications requiring higher degree of image refinement. For simple inspection tasks, silhouette images are adequate and binary system may serve the purpose. It may be appreciated that gray-scale system requires huge storage processing capability because a 256 x 256 pixel image array with upto 256 different pixel values will require over 65000-8 bit storage locations for analysis, at a speed of 30 images per second. The data processing requirements can thus be visualised. It

is, therefore, essential that some means be used to reduce the amount of data to be processed. Various techniques in this direction are :

(a) Windowing. This technique is used to concentrate the processing in the desired area of interest and ignoring other non-interested part of image. An electronic mask is created around a small area of an image to be studied.

Thus only the pixels that are not blocked out will be analysed by the computer.

(b) Image Restoration. This involves preparation of an image in more suitable form during the pre-processing stage by removing the degradation suffered. The image may be degraded (blurring of lines/boundaries ; poor contrast between image regions, presence of background noise, etc.) due to motion of camera/object during image formation, poor illumination/poor placement, variation in sensor response, poor contrast on surface, etc.).

The quality may be improved, (i) by improving the contrast by constant brightness addition, (ii) by increasing the relative contrast between high and low intensity elements by making light pixels lighter and dark pixels darker (contrast stretching) or (iii) by fourier domain processing.

Other techniques to reduce processing are edge detection and run length encoding. In former technique, the edges are clearly found and defined and rather than storing the entire image, only the edges are stored. In run-length encoding, each line of the image is scanned, and transition points from black to white or vice versa are noted, along with the number of pixels between transitions. These data are then stored instead of the original image, and serve as the starting point for image analysis.

(iii) Image Analysis.

Digital image of the object formed is analysed in the central processing unit of the system to draw conclusions and make decisions. Analysis is done by describing and measuring the properties of several image features which may belong to either regions of the image or the image as a whole. Process of image interpretation starts with analysis of simple features and then more complicated features are added to define it completely. Analysis is carried for describing the position of the object, its geometric configuration, distribution of light intensity over its visible surface, etc.

Three important tasks performed by machine vision systems are measuring the distance of an object from a vision system camera, determining object orientation, and defining object position.

The distance of an object from a vision system camera can be determined by stadimetry (direct imaging technique, in which distance is judged by the apparent size of an object in the field of view of camera after accurate focussing), or by triangulation technique, or by stereo vision (binocular vision technique using the principle of parallax). The object orientation can be determined by the methods of equivalent ellipse (by calculating an ellipse of same area as the image of object in two-dimensional plane, and orientation of object being defined by the major axis of the ellipse), the connecting of three points (defining orientation by measuring the apparent relative position of three points of image), light intensity distribution (determining orientation based on relative light intensity), structured light method (in which the workpiece is illuminated by the structured light and the three dimensional shape and the orientation of the part are determined by the way in which the pattern is distorted by the part).

Image can be interpreted by analysis of the fundamental geometric properties of two-dimensional images.

Usually, parts tend to have distinct shapes that can be recognized on the basis of elementary features. For complex three-dimensional objects, additional geometric properties need to be determined, including descriptions of various image segments (process being known as feature extraction). In this method the boundary locations are determined and the image is segmented into distinct regions and their geometric properties determined. Then these image regions are organised in a structure describing their relationship.

An image can also be interpreted on the basis of difference in intensity of light in different regions. Analysis of subtle changes in shadings over the image can add a great deal of information about the three-dimensional nature of the object.

(iv) Image Interpretation.

Image interpretation involves identification of an object based on recognition of its image. Various conclusions are drawn by comparing the results of the analysis with a prestored set of standard criteria.

In a binary system, the image is segmented or windowed on the basis of clustering of white and black pixels. Then all groups of black pixels within each segment (called blocks) and groups of white pixels (called holes) are counted and total quantity is compared with expected numbers to determine how closely the real image matches the standard image.

Statistical approach can be utilised to interpret image by identification of a part on the basis of a known outline. The extent of analysis required for part recognition depends on both the complexity of the image and the goal of the analysis. The complex images can be interpreted by use of Gray-scale interpretation technique and by the use of various algorithms.

The most commonly used methods of interpreting images are feature weighing (several image features and measured to interpret an image, a simple factor weighing method being used to consider the relative contribution of each feature to be analysed) and template matching (in which a mask is electronically generated to match a standard image of an object). In actual practice, several known parts are presented to the machine for analysis. The part features are stored and updated as each part is presented, until the machine is familiar with the part. Then the actual parts are studied by comparison with this stored model of a standard part.

Similarly mathematical models of the expected images are created. For complex shapes, the machine is taught by allowing it to analyse a simple part. Standard image-processing software is available for calculating basic image features and computing with models.

3.7.4 Function of Machine Vision

Lighting and presentation of object to evaluated.

- It has great compact on repeatability, reliability and accuracy.
- I.ighting source and projection should be chosen and give sharp contrast.
- Images sensor compressor TV camera may he vidicon or solid state.
- For simple processing, analog comparator and a computer controller to convert the video information to a binary image is used.
- Data compactor employs a high speed away processor to provide high speed processing of the input image data.
- System control computer communicates with the operator and make decision about the part being inspected.
- The output and peripheral devices operate the control of the system. The output enables the vision system to either control a process or provide caution and orientation information two a robot, etc.
- These operate under the control of the system control of computer

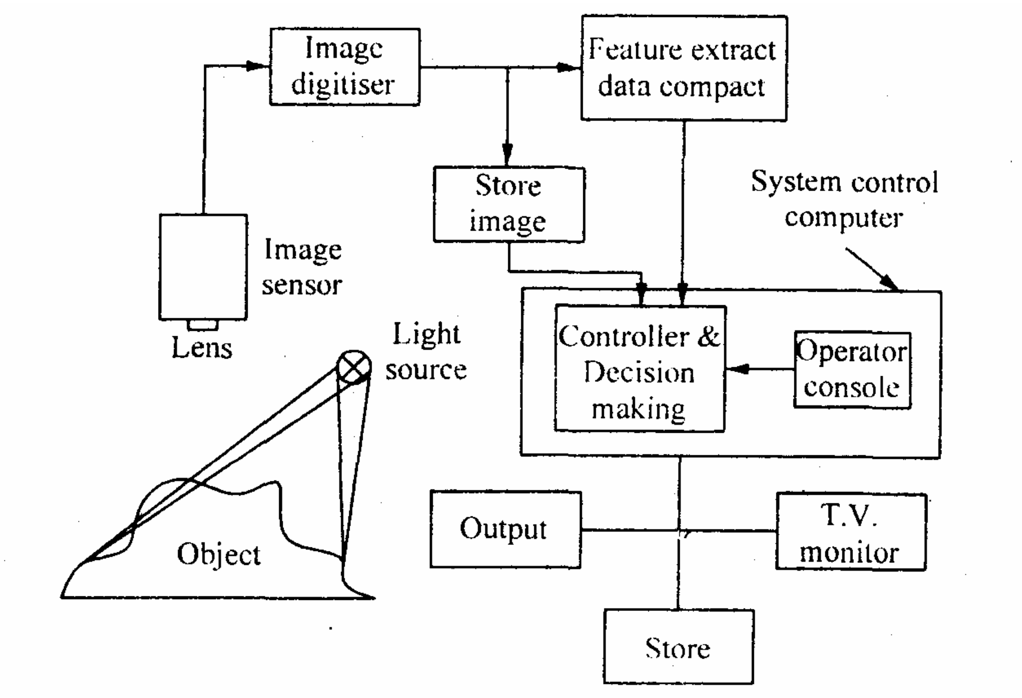

Fig. 3.52 **Block Diagram of Machine Vision Function**

[source: https://what-when-how.com/metrology/how-machine-vision-system-functions-metrology/]

3.7.5 Applications of Machine Vision in Inspection

Machine vision can he used to replace human vision fur welding. Machining and maintained relationship between tool and work piece and assembly of parts to analyze the parts.

- This is frequently used for printed circuit board inspection to ensure minimum conduction width and spacing between conductors. These are used for weld seam tracking, robot guideness and control, inspection of microelectronic devices and tooling, on line inspection in machining operation, assemblies monitoring high-speed packaging equipment etc.
- It gives recognition of an object from its image. These are designed to have strong geometric feature interpretation capabilities and pa handling equipment.

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 ascertain 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.