# ADVANCEMENTS IN DIMENSIONAL METROLOGY

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***Abstract* — Dimensional Metrology has been evolving ever since the measurement standards were established. The need to minimize errors and improve upon accuracy and precision has prompted Metrologists across the globe to innovate measurement techniques. Any object produced should comply with its designated dimensions to meet the functional requirements. The innovative methods adopted for checking dimensional compliance of objects is discussed in this paper. This paper gives a brief overview of improvements in Coordinate Measuring Machines, use of Scanning Electron Microscope and Computed Tomography towards dimensional metrology, advancements and challenges in Micro and Nano dimensional metrology.***

***Index Terms*—Dimensional Metrology, Co-ordinate Measuring Machines, Scanning Electron Microscope, Computed Tomography.**

## I. INTRODUCTION

All manufactured components around us undergo the essential three stages – design, analysis and manufacture. The investigation of a manufactured component for its compliance with the designed dimensions require metrology tools. The measurement of different dimensions to ascertain the shape and size of an object helps in assessing its designed functional capabilities. A product not conforming to the designed dimension may fail causing huge losses. The mechanical and optical tools are widely used for dimensional metrology these days. From simple Vernier Calipers to sophisticated Scanning Electron microscope, various tools are employed depending upon the required accuracy and precision. Metrologists are constantly trying to improve the existing tools, introduce tools employed elsewhere towards dimensional metrology and find innovative ways to measure in Micro and Nano scale.

The Coordinate Measuring Machine has been around for quite a long time now. Though it has been serving the requirements to satisfying levels, many improvements are being made to enhance its performance and measurement. This paper deals with such improvements in the next section. The implementation of Scanning Electron Microscope and Computed Tomography towards dimensional measurements is discussed next. Finally, dimensional measurements and prospective standards for measurement in Micro and Nano scale is discussed.

## II. COORDINATE MEASURING MACHINES

A Coordinate Measuring Machine (CMM) is a machine in which a measuring head equipped with a probe, having precise movements in the three co-ordinate directions – *X, Y & Z,* is used for measuring the dimensions in a Coordinate Space. The very first so called Coordinate Measuring Machine was developed by Ferranti, Ltd. in 1956. It was called as Ferranti inspection machine and Harry Ogden was instrumental in the invention. It had an accuracy of 0.025 mm and resolution of 0.012 mm. It had movement of 610 mm, 381 mm and 254 mm along *X, Y* and *Z* direction [1]. With the evolution of computers, the CMM were integrated with computers to store number of dimensions measured and obtain geometrical features from the data of points obtained.

Many patents are being filed regularly towards CMM design. Articulated arm Coordinate Measuring Machines, often abbreviated as ACMMs are widely sorted. They can measure a volume in spherical coordinates. In 1995, Faro Technologies Inc. filed a patent for a novel portable Coordinate Measuring Machine. It consisted of multijointed (preferably six joint) arm and serial box controller. The controller electronically interfaced computer to the arm. The arm could easily measure the volume accurately. Measured accuracy was $2\sigma \pm 0.005$ inch [2]. In Year 2000, a display device positioned on multijointed arm was patented. This device along with showing transducer position indication the three coordinate dimensions, also displayed system power and error status. The host computer sends signals through telemetry [3].

Attaching a retro-reflector to the articulate arm of a coordinate measuring machine and using a laser tracker to send laser beam to the retro-reflector was designed in 2010. The laser tracker located the position of the retro-reflector in the first Coordinate system with respect to the laser tracker while the articulated arm CMM gave the position of the retro-reflector with respect to the CMM. The CMM was capable of relocation to distinct positions while the laser tracker remained at fixed position [4].

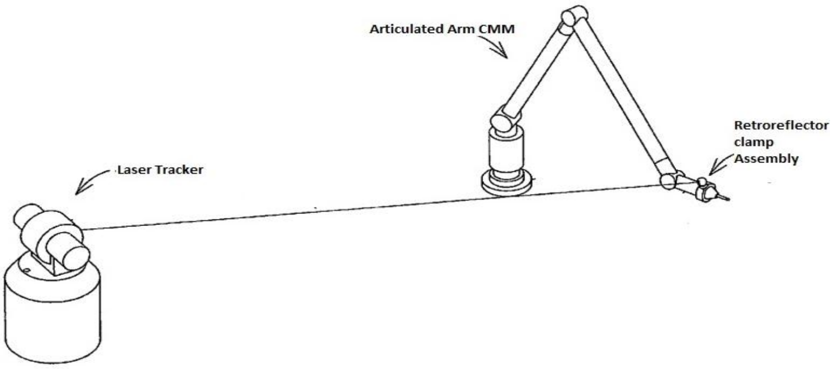

Fig 1: Retro reflector clamp assembly on an articulated arm CMM [4].

The probes have also undergone many developments. The elastic hinges carrying the probe stylus bends during measurement. This bending is sensed by a piezoresistive strain gauge. The 3D measurement is in the range of one hundred micrometers in *X, Y* and *Z* direction. The repeatability of the system is in the nanometer level. When compared with a laser interferometer, the uncertainty was in the order of 25 nanometers [5]. Combining the optical and mechanical systems a tactile sensing system was designed to measure objects in the sub micrometer level with good accuracy by H. Schwenke et. al.[6].

Measuring flatness using CMM has its own constraints. The probe measures different points on a surface. Measuring all the points on surface is tedious task and consumes more time. The sampling size and sampling method of points has a direct effect on accuracy of flatness. Increase in the sampling size decreases the flatness discrepancy rate like a unimodal function [7].

## III. OPTICAL METHODS FOR DIMENSIONAL METROLOGY

The vast demand for measuring dimensions has prompted Metrologists to use variety of optical machines used for other applications like medical diagnostics, towards dimensional metrology. In the recent times, the two most popular techniques is Scanning Electron Microscope and Computer Tomography.

### SCANNING ELECTRON MICROSCOPE:

The usage of Scanning Electron Microscope (SEM) for measurement of Integrated Circuit Chips in the sub-micrometer has been carried out [8]. Smaller linewidths and high aspect ratio structures has proven a major advantage for the use of Scanning Electron Microscope towards measurement of micro-electrical devices. Linewidths as small as 130 nm is achievable. SEM provides a very high resolution analysis and inspection than optical microscopes and scanned probe techniques [9]. Monte Carlo Method of modelling is adopted widely in SEM to obtain 1 dimensional, 2 dimensional and 3 dimensional measurements. The complexity involved in the interaction of electrons with solid has made scientists to adopt simulation models to obtain the measurements. The electrons lose their energy only after scattering several times and millions of electrons strike the solid at a time. Hence, Monte Carlo Method is preferred.

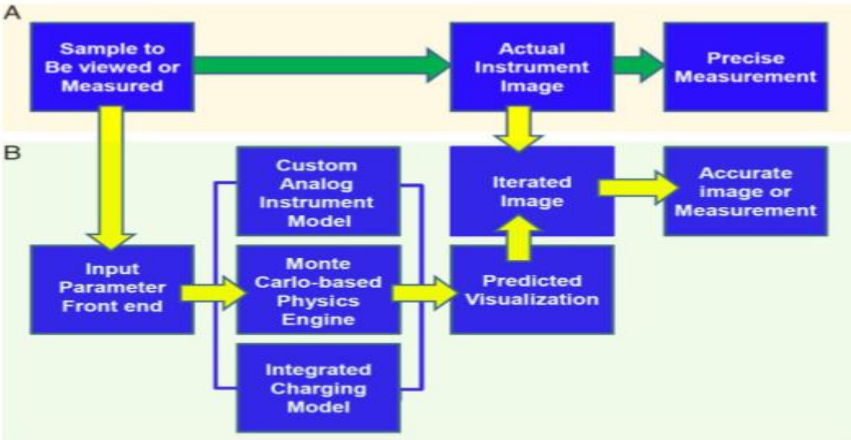

Fig 2: Process to improve the accuracy of measurement using Scanning Electron Microscope (SEM) [10].

The usual process of measurement using a SEM is as shown in Part A of Fig 2. The object sample to be viewed is subjected to image production by Scanning Electron Microscope and measurement is taken. This method gives measurement of higher precision. The semiconductor industry has exploited this straightforward measurement technique immensely. The highly precise measurement can be calibrated to a good accuracy using appropriate calibration samples. But obtaining highly accurate measurement directly out of Scanning Electron Microscope requires simulation modelling and Monte Carlo Modelling technique is the most preferred choice. As shown in Part B of Fig 2, Image and instrument modelling become evident. Physics based model is simulated for electron beam interaction and signal generation. The actual image is iterated with the model predicted visualization and measurement is taken accurately [10].

### COMPUTED TOMOGRAPHY

Computed Tomography (CT) scans which is primarily used for various medical diagnostics has been effectively employed for dimensional measurements. It is observed that Computed Tomography is the only technology in the present-day scenario capable of measuring inner and outer dimensions to the same level of precision and accuracy. The parts manufactured by Additive Manufacturing technique - a technique which is getting popular to produce parts with intricate designs are difficult to measure on the features are inaccessible. For such parts the Computed Tomography technique has been accepted for effective measurements. This method also helps to perform dimensional and material quality control simultaneously, which reduces the time taken in the quality check [11].

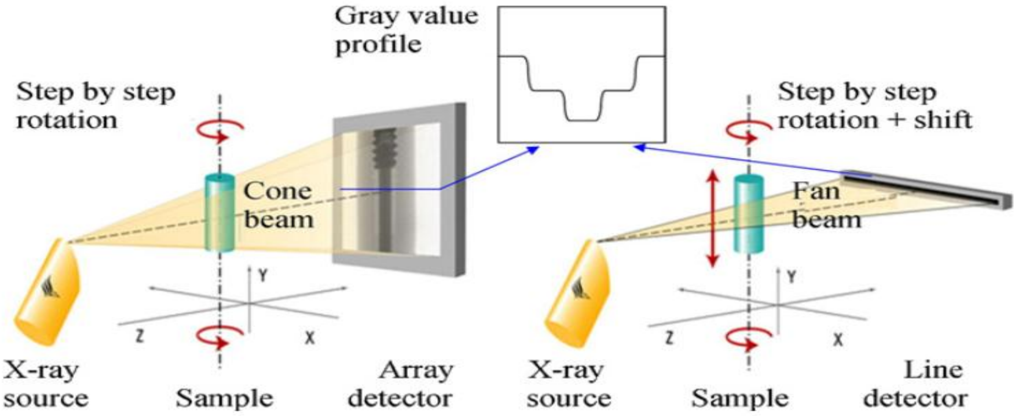

Fig 3: 2D Flat Panel Detector with cone beam and 1D Line Detector with fan beam [11].

The principle behind Computed Tomography is shown is Fig 3. A beam of X-Ray source is passed through the workpiece. The rays are absorbed or scattered to varying degree by the workpiece depending upon the internal form and material density in case of multi-material objects. The remaining rays are absorbed on the detector. The attenuation in the rays due to absorption or scattering is measured on the detector to produce a 2D gray image of the object in case of cone beam and 1D image in case of fan beam. The workpiece sample is rotated step by step to obtain the 2D images from different angles. The obtained images are then reconstructed mathematically to obtain voxel image. Subsequently from the post processing of the voxel image, dimensions and quality related data are obtained [11].

The accuracy and traceability of Computed Tomography systems is facing a challenge. Measurements made in sub-voxel accuracy has been deterring the form measurement accurately. Measuring length to system's specifications is also a challenge. International standards are to be established for proper measurement procedure to calculate uncertainty in Computed Tomography techniques [12]. Nonetheless, the Computed Tomography systems are finding wide applications in mechanical field right from manufacturing to quality control. Fig 4 shows one of the application where a comparison of manufactured part with its CAD model is made after getting the Computed Tomography scan of part. Other applications involve in fit analysis of plastic parts, metal molded parts, double threaded parts, multi material part analysis, additive manufactured parts with complex internal features, casted parts and dimensional quality control [13].

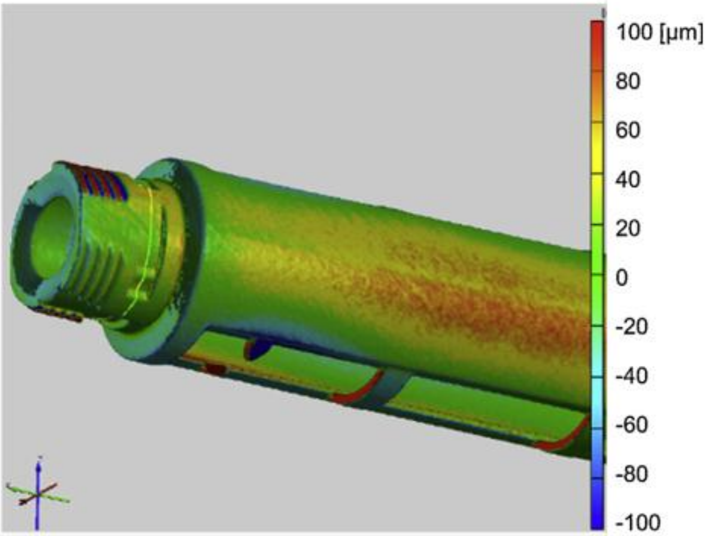

Fig 4: Comparison of Computed Tomography scanned manufactured part with its CAD model [13].

## IV. DIMENSIONAL METROLOGY IN MICRO AND NANO SCALE

The advent of Micro Electro Mechanical Systems (MEMS) and nanotechnology has made scientists and industrialists to invent tiny parts which are difficult to be measured by conventional Metrological instruments. They also pose challenges with respect to establishing standards in the tiny-scale range. But research has been carried out on Reference dimensional metrology using Scanning Transmission Electron Microscopy. In Reference Dimensional Metrology two methods are followed, one based on crystal lattice constant and the other based on the pitch of a feature pair applied to calibrate the Transmission Electron Microscopy. Critical Dimensions can be accurately determined by this process [14]. The different measurement tasks in the micro meter scale level involves determining the helix angle, cutting edge radius, tool radius on spherical end and rake face roughness as shown in Fig 5.

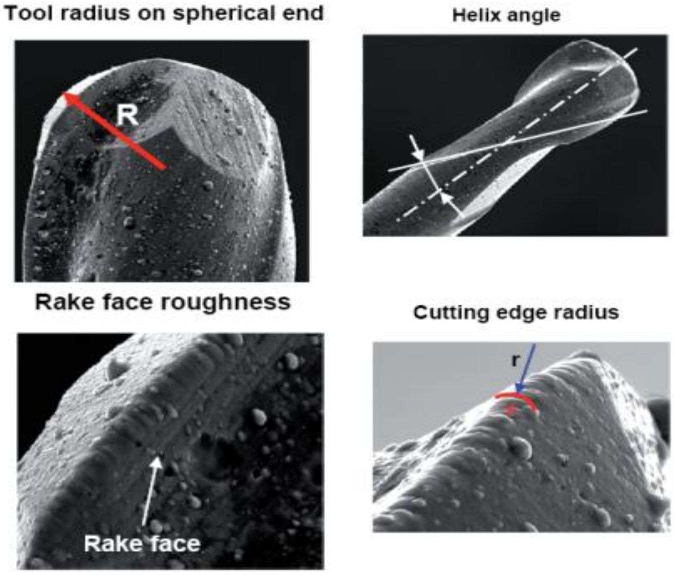

Fig 5: Measurements to be made on a tool in micro-meter scale [15].

The measurement of critical dimensions play a vital role in nanotechnology. These dimensions should correspond to the functional aspect of the part. There are inherent challenges in measuring such small components. Major areas of measurement include surface roughness, material composition of nano-composites and the likes. To standardize length and force in the nano-scale a proposal to consider human DNA as a metrology standard is given by John Peter Rickgauer et. al. Specific DNA molecules holds the advantage of replication by standard procedures [16].

## V. CONCLUSION

Coordinate Measuring Machines have been used extensively for measurement of shape and form of a component. The requirement of producing a component for narrow tolerances has paved way for improvements in the way components are measured. Scanning Electron Microscope and Computed Tomography have proved great alternatives, but they have their own limitations. Many improvements are also being carried on Coordinate Measuring Machines. Along with these improvements on existing machines, challenges in Micro and Nano scale measurement will encourage new inventions in the metrology field in the years to come.

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