International Journal of Computer Integrated Manufacturing,
Avaliable online 28 December 2025
DOI: 10.1080/0951192x.2025.2599551

Evolution and Application of Dimensional Metrology: A Comparative Review

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The final published version (version of record) is available online at DOI:10.1080/0951192x.2025.2599551.
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Abstract

Metrology, the science of measurement, has significantly evolved to meet the demands of modern industries. It is pivotal in advancing modern manufacturing by ensuring precision and quality. This paper explores the historical significance, technological advancements, and contemporary applications of metrology, highlighting key technologies like laser trackers, photogrammetry, interferometers, coordinate measuring machines (CMM), coordinate measuring Arms (CMA), electromagnetic distance measurement (EDM), and digital metrology tools. Each technology's unique capabilities, such as high precision, long-range measurement, and data integration, are compared, emphasizing their roles in fields like aerospace and manufacturing. The comparative analysis provides insights into the advantages and limitations of these technologies, offering guidance for selecting appropriate metrology solutions. Additionally, the potential future advancements in metrology, driven by innovations in sensor technology, artificial intelligence, and digital twins, are discussed. This paper accentuates metrology's pivotal role in enhancing measurement accuracy, reliability, and efficiency in various engineering and manufacturing processes.

Keywords: Retroreflector; Interferometry; measurement accuracy; precision engineering.

1. Introduction

Metrology has become an indispensable aspect of modern manufacturing, playing a crucial role in ensuring the reliability, precision, and quality of products across a wide range of industries. With the continuous advancement of manufacturing technologies, the demand for accurate and standardised measurement has intensified, making metrology more critical than ever.

Metrology encompasses a broad spectrum of activities, from the calibration of measuring instruments to the verification of product specifications and the development of new measurement techniques (Cerqueira Bastos, 2018). The importance of precise measurement in physics is well-established, and the same principles apply to the manufacturing sector, where the ability to reliably measure and control variables such as dimension, weight, and material properties is critical to the successful production of high-quality goods (Krismastuti & Habibie, 2022).

The concepts of precision, accuracy, uncertainty, and traceability are fundamental to the field of metrology and must be well-understood by both metrologists and users of metrological data. Precision refers to the reproducibility of a measurement, while accuracy relates to the closeness of the measurement to the true value. Uncertainty quantifies the range of values within which the true value is likely to lie, and traceability ensures that measurements can be linked to recognised standards or references (Larrabee & Postw, 1993).

Over the years, it has become increasingly important to miniaturise various aspects of technology, leading many industries to rely on metrology. For example, the semiconductor industry to achieve submicron-level dimensional control, essential to produce high-performance microchips.

By ensuring the accuracy and reliability of measurements, metrology helps to reduce waste, improve product quality (Cook, 1975), and enhance overall manufacturing efficiency (Akdogan, 2018). As the demands of the market continue to evolve, the field of metrology will undoubtedly continue to play a pivotal role in shaping the future of manufacturing.

This paper aims to provide researchers and other interested parties with comprehensive source of information on metrology, focusing on dimensional metrology. It begins with an overview of the history of dimensional metrology as well as an in-depth look into the current measurement technology, their measurement methodology, merits and demerits. It also considers how metrology has been applied in

current technological trends like precision engineering, Large-Scale dimensional metrology (LSDM) and digital twin technology, and how they can influence the future of manufacturing as we know it.

2. Historical Overview and Evolutionary Scope

Usually defined as the science of measurement, metrology has existed since humanity first developed the need to define, compare, and standardise quantities. Early societies recognised that reliable measurements were essential for trade, construction, agriculture, and astronomy, and so began to develop units that could be applied consistently within their communities. Over time, these units became part of cultural identity and governance, influencing economics, architecture, and even religious practices.

A prime example is the Babylonian civilisation, which created some of the earliest documented systems of measurement. They defined units for capacity (Sila), area and volume (Sar), weight (Mana), and length (Kush), providing a structured framework that supported commerce and infrastructure. The Egyptians also contributed significantly to early metrology. Observing celestial patterns, they discovered that every 365 days, coinciding with the annual flooding of the Nile, the Dog Star (Sirius) rose alongside the sun. This astronomical observation allowed them to create a 365-day calendar beginning in 4236 BCE, which is recognised as one of the earliest documented references to a solar year (Northeast Biomanufacturing Center & Collaborative, 2016). Their standardised cubit, based on the length of the pharaoh's forearm, further highlights how measurement was intertwined with daily life and monumental architecture such as the pyramids.

In the medieval era, units such as the foot and pound were introduced, often derived from the dimensions of the human body or practical trade needs. However, these were typically localised and varied from region to region, creating challenges in commerce and technological exchange. True development of metrology as a scientific discipline did not begin until the 18th and 19th centuries, spurred by the Industrial Revolution. With the rise of mechanisation, engineering, and international trade, industries increasingly required measurements that were precise, reproducible, and universally recognised.

This growing demand led to the establishment of formal institutions dedicated to maintaining and advancing measurement systems. For instance, the Bureau International des Poids et Mesures (BIPM) was founded in France in 1875 to oversee international standards (Bureau International des Poids et Mesures, 2019), while the National Physical Laboratory (NPL) in the UK was established in 1902 as a national centre for measurement science (Macdonald, 2021). These organisations played a crucial role in moving metrology beyond local traditions.

Today, metrology is more than just the definition of units, it encompasses scientific research, industrial application, and legal frameworks that ensure measurements remain accurate and traceable worldwide. It has become an essential foundation for progress in fields ranging from biomanufacturing and aerospace to digital technologies and healthcare.

3. Technological Advancements in Metrology

In recent times, the rising volume and complexity of components have placed greater demands on metrology systems, leading to the development of a wide range of devices for measuring various physical quantities such as length, time, mass, and temperature. etc (Lombardi, 2011).

Distance measurement has advanced from the use of anthropometric references, such as arm length, to the application of precise instruments offering improved accuracy and range. These instruments range from simple tools like steel rulers and Vernier callipers for short distances, to tape measures for longer distance measurements, Manual instruments for measuring length are shown below on Figure 1.

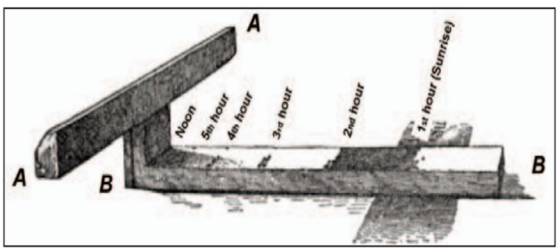


Figure 1. Egyptian shadow clock (Lombardi, 2011) and modern Distance measuring equipment.

Manual measurement instruments are considered reliable due to their typically analogue nature and independence from external power sources. Many of these tools offer remarkable accuracy and, when used correctly, can also provide good repeatability. The steel bar rule like the one shown on Figure 1 has a resolution of about 0.5mm, making it ideal for on-the-fly dimension verification. Other similar measurement instruments include in the Table 1 below:

Measurement Equipment	Resolution
Depth Micrometre	0.01 mm
Measuring Tape	1 mm
Gear Tooth Vernier Calliper	0.02 mm
Height Gauge	0.02 mm
Digital Vernier Calliper	0.01 mm
Dial Gauge	0.01 mm
Bevel Protector	1 degree
Inside Micrometre	0.01 mm
Vernier Calliper	0.02 mm
Screw Thread Micrometre	0.01 mm
Sine Bar	0.01 mm/m

Table 1. Resolution of manual measurement equipment (dcunite, 2021)

In the modern era, metrology has continued to evolve with the advancements in technology. However, one invention that has significantly influenced contemporary metrology is the interferometer.

3.1 Key Technology that Influenced Modern Day Metrology

Laser Interferometry

Interferometry is a technique that involves superimposing two or more waves to produce an output wave that differs from the individual input waves (Born & Wolf, 1999). It can also refer to a method or device that utilizes the interference patterns of these waves to calculate various wave-related parameters. Interferometry is widely used as a measurement tool in fields such as seismology, precision measurement, engineering metrology, and quantum mechanics.

In the 19th century, scientists such as Albert A. Michelson and Edward Morley developed the first interferometers to study light wave interference and to test the hypothesis of the luminiferous ether. (Freise & Strain, 2010).

The operation of an interferometer is illustrated in Figure 2. A beam splitter divides a laser beam from the source into two beams of equal intensity. The beams are reflected in different direction where they are incident on mirrors and are reflected to the beam splitter and merged. Due to the difference in path lengths between the two mirrors and the beam splitter, interference occurs between the returning beams. This interference results in a phase shift caused by a change in the optical path length. The resulting optical path length difference can be used to extract precise information, such as length.

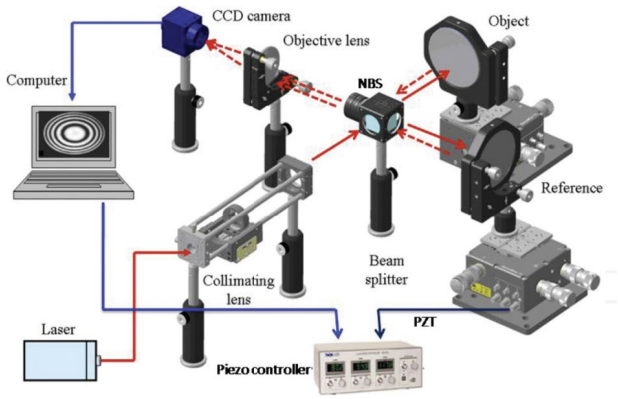


Figure 2. Schematic of the Twyman-Green interferometer (Abdelsalam & Yao, 2017)

Laser interferometers are capable of distance measurement with very high accuracy (up to nanometres). This high accuracy and resolution make it the technology of choice in engineering and optical metrology and an area of great research interest.

An application that clearly demonstrates the critical role of interferometric sensitivity in metrology is the detection of gravitational waves.

A gravitational wave was first detected on September 14, 2015, and is believed to have been generated by the collision of two black holes, resulting in the formation of a larger one (LIGO Lab, 2015). The signal was initially observed by the interferometer in Livingston, Louisiana, and subsequently by the one in Hanford, Washington. This dual detection eliminated doubts about the authenticity of the signal and provided strong confirmation of Einstein's 1915 prediction regarding gravitational waves as part of his general theory of relativity.

The sensors used by Laser Interferometry Gravitational-wave Observatory (LIGO) to detect these waves were giant Michealson Interferometers. One arm of the interferometer is made up of two mirrors suspended 2.5 miles apart, and a second arm perpendicular to the first is made up of two additional mirrors. A beam splitter directs laser light into the arms and distributes it among them. Before returning to the beam splitter, the light is allowed to repeatedly bounce between the mirrors.

The interference between the light beams returning to the beam splitter will point all the light back towards the laser if the two arms are the same length. However, if there is any variation in the lengths of the two arms, some light will travel to a photodetector where it can be captured (Rowan & Hough, 1999).

As the gravitational wave passes by, the space-time ripples alter the distance that a laser beam can measure. These variations are just approximately 10^{-22} cm, yet they are sufficient to alter the amount of light reaching the photodetector (Pitkin et al., 2011). Interferometers, along with technologies such as Absolute Distance Measurement (ADM) systems, have been employed to develop a range of measurement solutions used in industry to ensure dimensional conformity.

Laser Scanning & LiDAR

Laser scanning, also known as LiDAR or Light Detection and Ranging, is a remote sensing technique used to determine the distance to objects by emitting laser pulses and measuring the time it takes for the reflected light to return to the sensor. Its fundamental operating principle is time-of-flight measurement, in which the scanner emits a short pulse of laser light toward a target surface, the light strikes the surface and reflects back toward the scanner, and a sensor detects the returning light. The system then calculates the distance using the formula

$$Distance = \frac{c * t}{2}$$

where c represents the speed of light and t is the round-trip travel time of the laser pulse.

To establish precise spatial information, these distance measurements are combined with the scanner's orientation and position data obtained from GPS and inertial navigation systems, allowing the computation of accurate 3D coordinates for points on the object or terrain. By repeating this process millions of times per second, the system produces a dense three-dimensional point cloud that represents

the scanned environment, enabling detailed modelling, analysis, and visualization across a wide range of applications (Di Stefano et al., 2021).
Midrange terrestrial laser scanning (TLS) originated from space and defence applications, with significant funding from agencies such as DARPA and NASA between the 1960s and 1990s. Initially developed for remote navigation in hazardous environments such as war zones and space, TLS played a critical role in guiding unmanned vehicles and robots. The technology's roots trace back to the NASA Surveyor program, which identified the need for highly accurate sensors for planetary rovers, docking spacecraft, and other unmanned missions.
From the late 1980s onward, advances in microelectronics, corporate technology transfer initiatives, and evolving business cultures enabled TLS to transition into industrial and cultural heritage applications.
Early TLS systems, primarily time-of-flight (ToF) and phase-shift (PS) devices, were not intended to compete with surveying equipment but evolved into industrial surveying tools by the late 1990s. Before commercialization, TLS was deployed on satellites, space exploration vehicles, and autonomous land robots, providing computer vision for navigation and terrain modelling as a robust alternative to passive video and stereo imaging (Spring, 2020).
This technology is used today in metrology equipment like the laser scanner which is used to create point cloud data from scanned objects surfaces.

Optical Microscopy & Digital Imaging

Optical microscopy is a technique that employs visible light and a system of lenses to magnify and resolve fine details of a specimen, making it possible to observe and measure features at micro- and sub-micrometre scales. In its basic form, light from an illumination source is focused onto the specimen through a condenser lens. The transmitted or reflected light is then collected by an objective lens, forming a magnified intermediate image that is further enlarged by an eyepiece or projected onto an electronic sensor. The resolution and clarity of the resulting image are influenced by factors such as numerical aperture, optical aberration correction, and the quality of illumination. Advanced optical microscopy techniques such as phase contrast, differential interference contrast (DIC), fluorescence microscopy, and confocal microscopy enhance the ability to visualize and measure complex structures with high accuracy (Davidson & Abramowitz, 2002).
The integration of digital imaging technologies has significantly expanded the capabilities of optical microscopy in metrology. Electronic detectors such as charge-coupled devices (CCDs) and complementary metal oxide semiconductor (CMOS) sensors have replaced traditional photographic methods, enabling real-time image capture, digital storage, and advanced computational analysis (Murphy & Davidson, 2013).
Digital image processing facilitates quantitative measurements, dimensional analysis, and three-dimensional reconstruction of microscopic features. In metrology, the combination of optical microscopy and digital imaging allows for precise, non-contact measurement of surface geometry, feature dimensions, and defect characterization, making it invaluable in fields such as semiconductor manufacturing, materials science, precision engineering, and biomedical research. Together, these technologies provide a powerful platform for accurate measurement, quality control, and documentation at microscopic scales.

Holography & Speckle Interferometry

Holographic interferometry is a contactless metrology and non-destructive testing technique that measures displacement or deformation by recording and comparing the optical wavefront of an object at different states. In its typical setup, a laser beam is split into two parts: the object beam, which illuminates the object and carries both amplitude and phase information, and the reference beam, which bypasses the object and directly reaches the sensor. The interference between these beams creates a hologram, and by capturing holograms at two instants and extracting the phase difference, surface displacements can be determined. Digital holography modernizes this process by replacing analogue photographic plates with digital sensors and reconstructing the object wave numerically through diffraction algorithms (Georges et al., 2019).
Speckle interferometry operates on a similar principle but relies on the random interference patterns generated when coherent light reflects off a rough surface, with the object's image formed through an

imaging lens. Two specklegrams, taken before and after deformation, are processed with a phase-shifting algorithm to extract displacement information. While Speckle interferometry is naturally suited for scattering surfaces, it can be adapted for specular surfaces by using a diffuser to mimic scattering behaviour. For objects combining scattering and specular regions, each area is analysed using its own sensitivity vector, and special illumination arrangements diverging beams for scattering areas and diffuser-based beams for specular ones allow simultaneous measurement of both surface types. (Ganesan, 2009).

Emerging soon after the invention of the laser in the 1960s, Holographic interferometry and Speckle interferometry quickly established themselves as powerful, non-contact measurement methods. Through the 1970s to 1990s, they matured with the introduction of phase-shifting techniques, better coherence control, and key adaptations for specular surfaces, such as Hansen's diffuse illumination approach. The shift from film to CCD/CMOS sensors in the 2000s enabled numerical wavefront reconstruction and expanded the use of digital holography into infrared wavelengths, particularly the long-wave infrared range, which facilitates measurement of large deformations. Today, these methods remain vital to metrology, offering full-field measurements that surpass the single-point capabilities of contact probes, enabling the analysis of delicate or space-bound components without altering their surfaces. Their ability to handle mixed reflectivity surfaces is particularly valuable in aerospace optics and composite structures, and their integration with coordinate measuring machines (CMMs) enhances structural testing, predictive maintenance, and simulation validation by providing detailed deformation and strain maps across entire surfaces in a single acquisition.

Computer-Aided Metrology

Computer-Aided Metrology is the application of computer-based tools, software, and automated measurement systems to enhance precision, efficiency, and repeatability in dimensional inspection and quality control. As computers have evolved in processing speed, advanced graphic cards, multiple data formats etc, companies have taken the advantage to develop metrology software that make the measurement and inspection process easier. Software like PolyWorks, Spatial Analyzer, Verisuf etc have hardware and software integration easier.

By integrating technologies such as coordinate measuring machines (CMMs), laser scanners, photogrammetry, and advanced data and point cloud analysis software, computer-aided metrology enables rapid acquisition and processing of complex geometric data. This approach allows for real-time comparison of manufactured parts against digital models, streamlines production workflows, and supports closed-loop manufacturing processes. Widely used in aerospace, automotive, and high-precision engineering, it ensures that components meet stringent tolerances while reducing inspection time and minimizing human error.

Several other technologies have significantly influenced the advancement of dimensional metrology. Among these are time-of-flight (ToF) sensors, which determine distances by measuring the travel time of light or sound pulses, enabling rapid and precise three-dimensional mapping. In the area of environmental control and compensation, specialized systems have been developed to maintain measurement accuracy by minimizing external influences. This includes vibration isolation technology, which ensures stability for nanometre-scale measurements (Xie et al., 2021), and air quality and pressure monitoring, which are particularly critical for interferometry and the maintenance of precision length standards (Z. Wang et al., 2025).

3.2 Measurement Solutions

In the ever-evolving landscape of scientific research and industrial applications, the importance of accurate and reliable measurement solutions cannot be overstated. Over the years, various industries have become so reliant on these tools that their operations would be impossible without them. As a result, there are several measurement equipment for several applications.

Electromagnetic Distance Measurement (EDM)

Distance measurement has evolved past the simple measurement devices mentioned on table 1. In recent times, they have been used in applications not just limited to manufacturing but also in structural engineering (Y. Liu & Bao, 2021). These include wind turbine blade evaluation (Poozesh et al., 2020),

vibration monitoring in structures (de Oliveira et al., 2019) and even for delicate fields like non-destructive testing of medical equipment (Yadav et al., 2022).
EDM equipment rely on electromagnetic radiation to measure dimensions. Electromagnetic radiation is characterised by a sinusoidal wave form which repeats every 360° (Bastola et al., 2021). EDM calculates for distance using the phase difference between two waves. The velocity of the electromagnetic wave is given by Equation below:

$$V = F\,\lambda$$

V = velocity of electromagnetic energy (m/sec)
λ = distance between wave form ends, wavelength (m)
F = modulated frequency of energy (Hz)
The Total Distance travelled by the wave is given by L

$$L = n\,\lambda + p$$

Between the time the signal travels to and from the reflector, it goes through "n" number of full phases. There is an angular difference between the outgoing and incoming wave resulting in a partial wavelength p.
The advantages of EDMs include its ability to measure long distances, microwave EDM instruments have a range of up 100km while Light and infrared wave EDMs offer between 2.5 and 3 kms range (Usman, 2014). Unlike other distance measurement equipment like rulers and calliper, they are relatively easy to use and have direct measurement data transfer hence limiting the possibility of errors. However they are considered to have high cost of equipment and measurement can be influenced by the weather, the size and transport of equipment is also a challenge.
Typical system setup is seen on Figure 3 below.

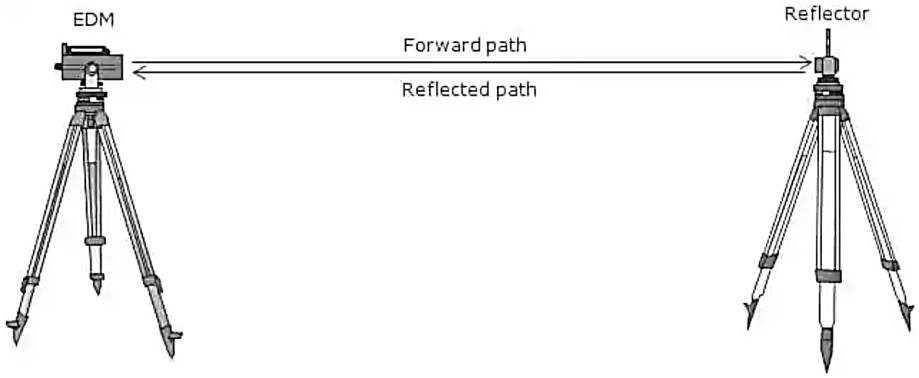


Figure 3. Setup of an EDM and a reflector (The Constructor, 2016).

EDMs work with reflectors, a study by Garthwaite et al., (2015) defined a radar reflector as a passive device that reflects incoming electromagnetic energy directly back to the source of that energy. In normal metrology application, it will be some arrangement of reflective surfaces to form a corner reflector capable of reflecting electromagnetic radiation back to its source. It could be as simple as a plane mirror. By applying the laws of reflection, several plane mirrors can be arranged, and the angle of incidence and refraction manipulated such the refracted ray is sent back to the source of the incident ray. The different types of corner reflectors include spherical reflectors, cylindrical reflectors, dihedrals, etc. When a microwave is used in this application, the reflector captures the incoming microwave and transmits it to the source.

Laser Trackers

A laser tracker is a portable coordinate measuring system that measures a stationary or moving target in a spherical three-dimensional coordinate (Hu et al., 2021a). The radial distance is measured by an interferometer or an absolute distance meter. Laser trackers incorporate an angular measurement system, a ranging system, a laser receiver, and usually require a computer with measurement software to work. Laser trackers also come with temperature probes which allow ambient or object temperature

readings to be taken and used to compensate measurements. The laser beam from the tracker is controlled to lock onto the trackers target by an actuated gimbal system. Angle encoders provide azimuth and elevation angles (Hughes et al., 2011). Over time, laser trackers have developed into accurate and effective instruments for tracking and measuring things in a variety of industries. Although its history can be traced back to the 1960s, laser trackers became available for industrial application in the late 1980s (Daniel Moser, 2019). There have been several improvements in the technology especially in accuracy where impressively tiny error values are still being improved upon (Hu et al., 2023). To achieve interferometry level accuracy, laser trackers work with the concept of laser interference to measure distance. Range errors are the main source of measurement error in laser tracking systems. To control or limit measurement errors, laser trackers use network measurements. A grating disc utilising the concept of multiple-slit diffraction is used in laser trackers enabling them to give accurate measurements up to (± (15 µm + 6 µm/m)) over a distance of 80m (Hu et al., 2023). Trackers like the AT960 from Hexagon metrology can operate within 15 microns over a 2 m distances and up to 500 microns at about 80m distance.
Although an ISO international standard is in the works (Motta de Souza et al., 2023) (B. Muralikrishnan et al., 2013), there is no standardised method of accessing the accuracy of a laser tracker. They are usually tested using ASME B89.4.19, VDI/VDE 2617 sheet 10(R. Kupiec et al., 2013).
They are ideal for high precision applications, like robot assisted manufacturing, railway construction (Hu et al., 2021b). Measuring deformation in subway tunnels (Cui et al., 2019) and even checking the accuracy and repeatability of precision equipment like robots (Slamani et al., 2012).

Laser Tracker Targets (Retroreflectors)

Laser tracker targets are essential metrology components that increase the versatility of the laser tracker. To measure the coordinates of a point, a laser tracker sends out a laser beam which is bounced back by a target attached to point. The angles and the distance to the target are measured by the tracker to derive the coordinates of the location. An interferometer or an absolute distance metre, is used to measure the distance (Cruz & Plakhov, 2015). This returns the XYZ coordinates of the point with respect to a predefined global frame.
Retroreflectors serve as laser tracker targets. The target's main objective is to reflect laser beams off its varied geometric surfaces with the greatest intensity possible while avoiding beam distortion as this may influence the interpretation by the interferometer or absolute distance meter. To deliver on the high measurement accuracy expected from the laser tracker system, the targets are manufactured to a near perfect geometry. Precision optics, precious metals, high-performance adhesives, and nearly perfect geometry are all combined into intricate mechanical devices that serve as laser tracking targets.
Due to the high accuracy expectations, it is very challenging to first manufacture and maintain the efficiency of these targets. After manufacture, they are usually subjected to several performance tests to ensure that the required build tolerance is met. Even a slight manufacturing error can cause measurement error (Junqueira Leão et al., 2014). And during use, it is very important to ensure that they are not subjected to severe conditions as this may cause material property changes which will in turn influence the measurement. Targets are subjected to falls during use and this may affect (crack) the reflective surface or change the position of the structure. Dust layers from different sources sometimes cover the reflective surfaces and can cause a change in the refractive index of the reflective surface on the targets. There are different types of retroreflectors, and they vary in their applications. The three most common types include cat eyes, repeatability targets and spherically mounted retroreflectors (SMR).

Spherically Mounted Retroreflectors (SMR)

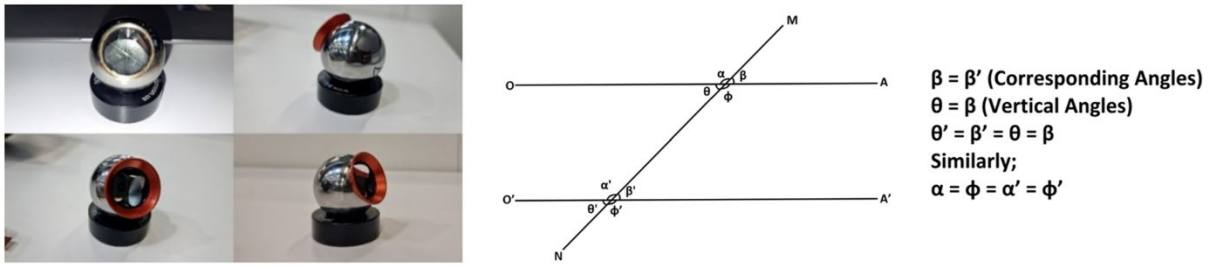
SMRs is one of the most common types of laser tracker targets. They are used in both large and small scall applications. A typical SMR design is a metallic magnetic sphere with a cutout where a corner cube retroreflector (CCR) is placed. The high accuracy expectation dictates that manufacturing process of highest quality is used for making the SMR. From the spherical metals to the reflective surfaces, the geometry of the parts needs to be as close to design as possible, else this may introduce errors in the laser tracker measurement system. The metallic sphere is designed to seat on special SMR next which they perfectly balance on as seen on Figure 4(a). The spheres are designed for specific SMR diameters

(usually the 1.5” and the 0.5”). The magnetic force between them ensures that the next can be placed vertically without the SMR falling off. Steel spheres grade 25 is a typical ball grade for an SMR. A grade 25 ball has tolerances of +/-.0001" for diameter and a maximum of.000002" for surface roughness (Faro, 2021). Any material deformation on the next or the SMR can result in measurement errors (Junqueira Leão et al., 2014). Deviation can be caused by rusting of the sphere/next or from application of force.

Some very important SMR design properties include Centring of optics, Sphere properties, Dihedral angle error, Maximum dihedral angle difference, Wave front distortion, Polarization. (Faro, 2021)

The Corner Cube Reflectors is another major component in the SMR. A corner cube reflector is formed when three reflecting surfaces are placed at a 90 degrees angle to each other so that they are mutually orthogonal as seen on Figure 4 (a) and (b). This leads to the creation of an optical device capable of creating a reflected ray that is completely parallel to the incident ray but in the opposite direction (Voronov et al., 2016). This makes it ideal in applications like long-path interferometry, ranging, laser resonators and atmospheric absorption.

In Figure 4(b), lines OA and O’A’ are completely parallel. Line MN cuts across both. The relationship between the angles formed by the lines shed light on how a corner cube retroreflector is able to reflect a laser beam that is parallel to the incident beam.



(a) (b)

Figure 4. (a) 1.5’’ SMR on Drift next (from Hexagon) (b) Alternate interior and exterior angles

Specular Reflection

When light waves hit an opaque or irregular surface, it is absorbed by the surface due to physical properties of the body that permits absorption of certain wavelengths and frequencies of light. In other cases when light wave bounces on a surface, it is scattered at different angles. This is known as diffuse reflection. It helps the observer in image formation. Smooth mirror-like surfaces however do not scatter incident light waves. The light waves are reflected together at the same angle, creating specular reflection.

In a corner cube reflector, it is assumed that the reflective surfaces exhibit specular reflection the angle between them are 90 degrees. This ensures that the incoming and outgoing beams are parallel as seen in Figure 5 (d) below.

Corner cube reflectors have the tendency to get damaged over a period of use. The angle of the three reflective surfaces to each other can change if the adhesive holding them together degrades overtime. this can lead to Adjacent angle error (runout issues occur when the tracker tries to lock into the SMR's centre), total error (the beam is reflected in different direction not parallel to the incident beam), or wavefront distortion (panels are not flat). This can render the retroreflector unusable or reduce measurement efficiency.

Cateye Targets

The most common design for this rare and costly tracker target (Faro, 2021) consists of two solid glass hemispheres. Cat’s-eye retroreflectors provide the advantage of a wide acceptance angle and, unlike corner cubes, are less prone to errors such as signal loss and transverse shift.

As seen on Figure 5 (a), a common design for cat-eye retroreflectors involves fusing two concentric hemispheres of different diameters together. The equation bellow is used to relate the radius of the hemispheres. Takatsuji et al. (1999), designed a cateye retroreflector where the diameter of the two hemispheres is the same. A refractive index (n) of 2 was achieved allowing for R1 = R2.

$$R2 = (n-1)R1$$

The retroreflector had no issues of hemisphere centre misalignment or any issues with the adhesive used to fuse them together.

As seen on the equation bellow Coating the entire surface of the retroreflector leaves a total reflectivity of

$$R_{total} = R(1-R)^2$$

The value of R could be adjusted to achieve a total reflectivity of 14.8%, however, an uncoated design was successfully achieved, exhibiting a total reflectivity of 8.77%.

The reflector was tested by trying length measurement and motion tracking and it performed to satisfaction. The sphericity of the sphere was measured using the contacting stylus of a roundness measuring machine. This was important as the sphericity is a factor the influence the directional dependence of the retroreflector. The error in measurement for this reflector was experimentally determined to be 500nm. This reflector could be measured from any angle compared to conventional cateye reflectors that have an acceptance angle of ±75° (Hexagon Metrology, 2024b).

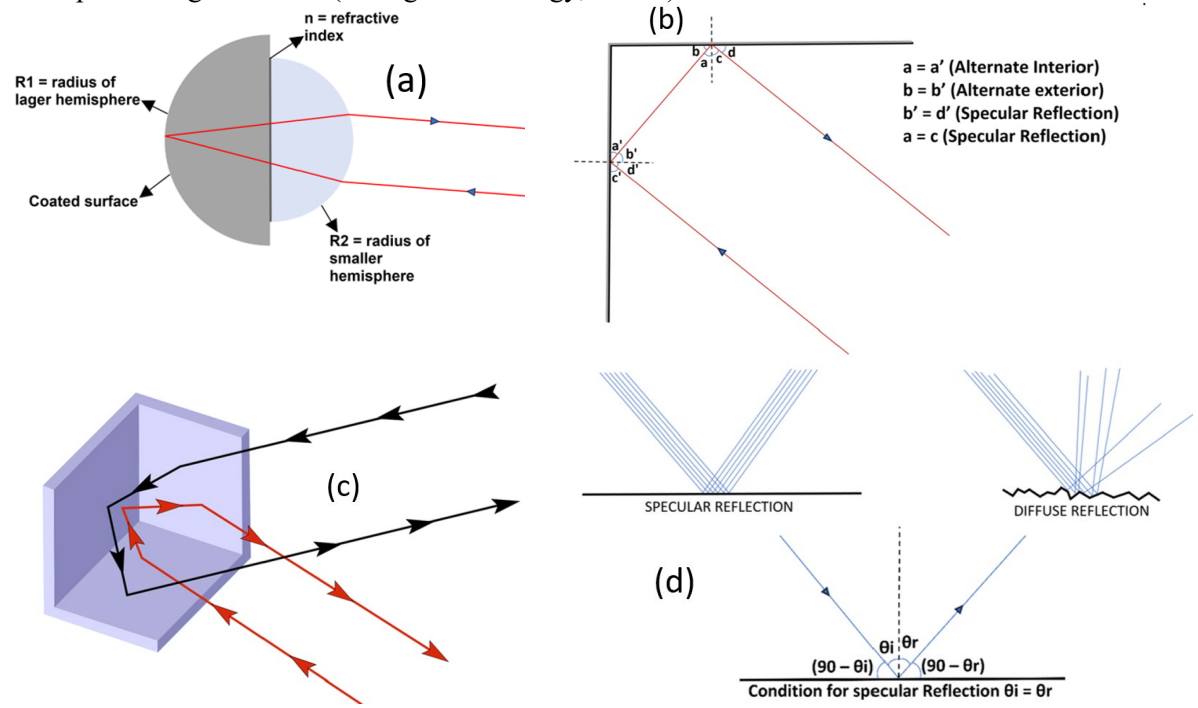


Figure 5. (a) Cateye Retroreflectors with different hemisphere radius (b)Corner cube reflection (2D), (c) 3D corner cube reflection (Voronov et al., 2016) (d) Specular and Diffused reflection

There are several laser tracker options available in the market. The most popular options are from Leica, Faro and API.

The FARO Vantage Laser Tracker is positioned in the higher-end segment of the market, whether purchased new or used, with prices often reaching tens of thousands of dollars. It offers a measurement accuracy within ±0.075 mm (75 µm) across large working volumes, making it a reliable option for applications that demand precision but also require versatility in operational range. Its compact, portable form factor allows it to be easily deployed in a wide variety of industrial settings, enabling on-site measurement and inspection without compromising measurement integrity. it boasts a range of up to 80m.

The API Radian Laser Tracker is another expensive and high-quality laser tracker, delivering industry-level accuracy. Capable of taking measurements up to 80m, it is a good option for the most demanding

metrological tasks, such as robotics calibration or ultra-precision assembly. Its design emphasizes portability, with a smaller and lighter build than many of its competitors, making it exceptionally well suited for field operations where high precision and ease of transport are critical.
The Leica Absolute Tracker shares the high-end pricing of the FARO and API models but distinguishes itself through a combination of accuracy and range (up to 160m). With a precision of approximately 15 µm, it meets the stringent requirements of advanced manufacturing sectors, including aerospace and automotive assembly. Its all-in-one, compact construction is engineered for durability, enabling reliable performance even in challenging industrial environments.

While laser trackers have become indispensable in large-scale dimensional metrology due to their high accuracy, portability, and range, they are also subject to several limitations. Line of sight dependency is a critical constraint; any obstruction between the tracker and the target retroreflector interrupts measurement, making reflector placement important. Sometimes multiple trackers may be required to cover a large inspection cell. Laser tracker accuracy degrades over long distances, especially in environments with fluctuating temperature, pressure, or humidity, as atmospheric refraction alters the laser beam path. Whether from the floor, mounting surface, or the target, vibration and mechanical instability can introduce noise and reduce repeatability, making Laser trackers less ideal for environments with significant mechanical activity. Measurement speed is also lower compared to full-field optical scanning methods, as trackers gather data point by point. Also, cost remains high, not only for the instrument but also for operation, since skilled personnel are required for setup, calibration, and data interpretation.

Photogrammetry

Photogrammetry, a technique for extracting precise measurements and quantitative data from photographic images, has a history that dates back to the late 1830s. During this time, the pioneer of photogrammetry, Frenchman Aimé Laussedat, developed the first practical applications of this technique (Polidori, 2020). Photographs taken from two different angles were used to create accurate topographic maps, revolutionizing the field of surveying. The first photogrammetric cameras were introduced in the 1850s for architectural measurement and digital cameras and software programs were developed in the 1990s to aid in image processing and 3D modelling.
Over the years, photogrammetry has evolved and advanced with the development of new technologies, this have seen an improvement in parameters like precision and accuracy. The precision of point measurement can be as high 0.1 mm for a range of 10 m (Luhmann, 2010) and that of length measurements can be about 0.05 mm for a 2 m range (Rieke-Zapp et al., 2009). Today, it is widely used in various fields such as quality control (Boesemann, 2000), in-line inspection of products on conveyor belts (Bergström et al., 2016), cartography, architecture (Werner & Zisserman, 2002), archaeology and building inspection (Ballard & Tuchscherer, 2016), large volume inspection like ships (Niebylski, 1997) and wind turbines (Baqersad et al., 2017).
Photogrammetry uses 2D images obtained from cameras to generate 3D data. The two types of photogrammetry are aerial and terrestrial photogrammetry. Aerial photogrammetry involves taking pictures of the object using satellite, helicopters or drones while terrestrial photogrammetry involves taking pictures on the ground close to the object (Stojakovic, 2008).
To be used as a metrology solution the 3D images created need to accurately represent the dimension of the object being pictured by the camera. As seen in Figure 6 (a) below, instead of just converting 3D images to 2D images like is done in photography, photogrammetry reverses this process.
It transforms or maps the two-dimensional flat images back into the actual three-dimensional form. Information is lost during this process effecting the accuracy of the process. To recreate the three-dimensional reality, at least two separate pictures are required, these pictures are required to clearly capture the object to be measured and the markers placed on it, the photogrammetric system is able to extract the spatial position of the camera and the markers. The number of 2D pictures used play a role on the quality of the 3D data generated. In an ideal scenario, two images would have more than enough information to recreate the three-dimensional scene that they depict although this is not always the case (Geodetic Services, 2017).

Over the years, researchers have found that the concept of photogrammetry can be applied to obtain dimensions in various application. Veldhuis & Vosselman (1998), presented two models that make it possible to reconstruct both straight and curved pipes from digital photographs. The centre lines in the photos had to be calculated before the straight pipes were rebuilt, which was a significant drawback. To solve this, the radius of the pipe was used as an additional unknown parameter to extend coplanarity constraint. Tests were run on a series of photos from various pipelines to validate this model. The influence of factors like the number of photos, camera placements and spatial distribution, and distribution of these measurements along the pipe's edge on the least-squares adjustment could be identified from the pictures. Consistent approximation and modified parameter values were obtained from various sets of observations, and flaws in the observations were simple to spot. And line photogrammetry appears to be reliable and durable.

Bösemann (2016), discussed the increasing relevance of industrial photogrammetry as a measurement tool in the manufacturing industry. The move from niche metrology application to an industrial solution was driven by advances in digital camera technology and processing power. Large-scale photography was combined with digital scanning technology by creating digital tools for image measuring and camera calibration. Key advantages of industrial photogrammetry like high portability, ability to measure multiple points simultaneously, and suitability for dynamic and unstable environments was highlighted. An example of an industrial photogrammetry equipment from Hexagon Metrology is seen in Figure 6 (b) below.

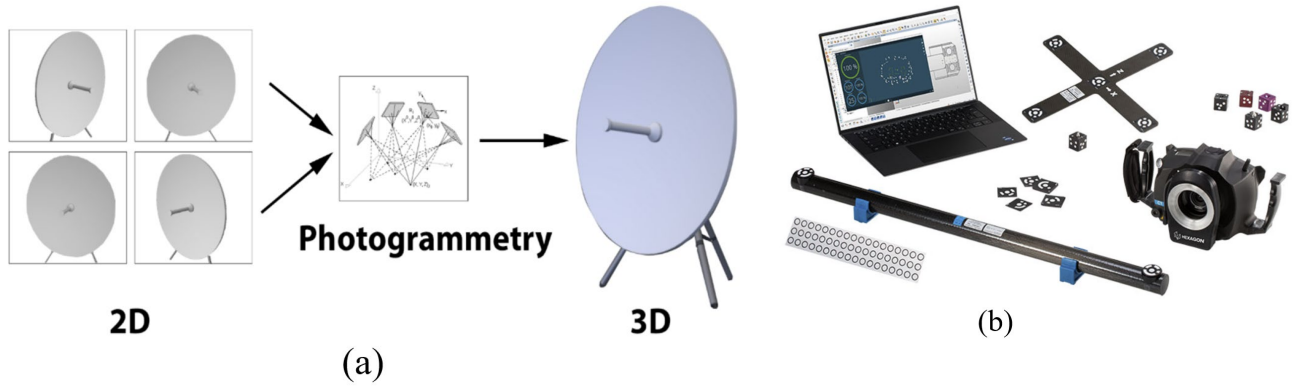


Figure 6. (a): Converting 2D image data to digital 3D using photogrammetry. (Geodetic Services, 2017) (b) DPA Pilot software platform, C1 50-megapixel digital camera (Hexagon Metrology, 2024a).

Photogrammetry is quickly becoming the culturally accepted form of metrology as my non engineers and surveyors use it for applications like converting statues to 3D models, this is not only because of researchers interest in reducing the process complexity (Almagro, 2002), but has a lot to do with the fact that most mobile devices today are equipped with cameras which are the data acquisition hardware and the availability of applications that can process captured images on mobile devices. The research interest in both improving it with artificial intelligence (Maroun et al., 2022) and fusing it with LiDAR (Gil et al., 2013) is also growing, putting photogrammetry in a position to be the metrology option of the future.

Photogrammetry is subject to several limitations that can affect accuracy and reliability. One major concern is image quality, as factors such as lens distortion, sensor noise, and poor lighting conditions can introduce systematic errors into the measurement process. Low texture or repetitive patterns on the object surface can also hinder feature detection and matching, leading to gaps or inaccuracies in the reconstructed geometry.

Environmental conditions play a significant role in photogrammetry performance. Variations in lighting, reflections from glossy surfaces, shadows, and environmental instabilities such as vibration can all degrade image consistency between frames. For outdoor applications, changes in weather or

sunlight position during data capture can lead to inconsistent image exposure and contrast, reducing the accuracy of the generated 3D model.
Calibration and processing challenges can impact measurement precision. Camera calibration errors, whether intrinsic (focal length, principal point) or extrinsic (position, orientation), propagate through the reconstruction process, particularly in large-scale projects. The computational load for high-resolution, multi-image datasets can also be significant, requiring powerful processing hardware and advanced algorithms. These issues can necessitate careful planning, controlled data acquisition, and rigorous calibration to achieve the high levels of accuracy expected in engineering and industrial metrology.
In addition to hardware and environmental constraints, photogrammetry is vulnerable to algorithmic accuracy limitations that can affect the reliability of reconstructed 3D data. Algorithmic accuracy issues arise when the computational processes used to reconstruct 3D geometry from images introduce systematic or random errors that degrade measurement precision. These issues often stem from limitations in camera calibration, feature detection and matching, bundle adjustment, and image geometry modelling.
Although it is used in more areas than other dimensional metrology options, it still presents its set of challenges in such area.
In under water photogrammetry, Optical degradation due to light absorption and scattering, particularly the rapid loss of red wavelengths, results in colour imbalance and reduced image clarity. Turbidity from suspended particles and dynamic caustic patterns caused by surface refraction further distort imagery and disrupt feature matching. Image acquisition is sometimes affected by very short camera to object distances, wave induced instability, and buoyancy control issues, all of which introduce scale inconsistencies and increase data volume. On the processing side, large datasets impose high computational demands, while inconsistent illumination and colour variations hinder the performance of structure from motion and multi-view stereo algorithms. These factors often necessitate advanced preprocessing, such as convolutional neural network-based caustics removal, to ensure accurate feature detection, reliable matching, and high-quality 3D reconstruction (Agrafiotis et al., 2018).
In aerial archaeological photogrammetry, ensuring adequate image overlap, typically around 90% frontal and 80% side, is critical; insufficient overlap can prevent reconstruction in photogrammetric software. Variations in camera mounting angles, flight heights, or grid patterns can distort spatial resolution and geometry. Environmental factors such as lighting direction, shadows, and weather conditions can further degrade image quality. Camera settings also play a major role, with inappropriate shutter speed or exposure leading to blurring, noise, and loss of detail. Rolling shutter distortions, often caused by vibration, can warp structural features and reduce precision. These factors often necessitate repeat flights, increasing time and cost, and require careful planning and calibration to achieve high-quality results (Desa et al., 2021).

CMMs and CMAs

Coordinate Measuring Arms (CMAs) and Coordinate Measuring Machines (CMMs) are among the most widely used and highly regarded metrology tools in modern industry. They play a crucial role in dimensional inspection, enabling precise measurement of complex geometries to ensure product conformity with design specifications.
Best known for their high accuracy and exceptional flexibility (Gapinski et al., 2006), CMMs have become one of the most dominant metrology solutions in use today. A CMM is a precision measurement device designed to determine the spatial dimensions of objects by capturing discrete points on their surfaces using various probing technologies, including laser, mechanical, and optical probes (Nikam, 2018).
Probe positioning in a CMM can be controlled either manually by an operator or automatically through computer control. In both cases, the probe's position is referenced to a Cartesian coordinate system, enabling precise translational and rotational motion along the three principal axes (X, Y, and Z). A typical CMM comprises four main components: the machine body, the probing system, the machine control hardware, and the measurement calculation software (Artkin, 2022a)

There are different types of Coordinate Measuring Machines (CMMs). Bridge CMMs are the most common configuration, offering high accuracy and structural stability, and are typically employed in controlled environments to achieve precision measurement. Cantilever CMMs feature an open-access design, making them ideal for measuring smaller components with quick loading and unloading. Gantry CMMs are designed to handle very large components, providing high accuracy over expansive measuring volumes, and are frequently used in aerospace and heavy industry. Also, Horizontal Arm CMMs are well-suited for measuring large complex parts such as automobile bodies, delivering both accessibility and flexibility in part positioning.

CMMs can be used for measurements ranging from the most basic applications like measuring diameter and length, to the most intricate tasks, like measuring free-form parts, automotive engines, gears, large turbines, or the turbine of a jet propulsion engine. Measuring arms, which are flexible like a human arm, can reach into the insides of complex parts that are inaccessible to conventional three-axis machines. These portable high-precision tools are particularly useful in process control, statistical data collection, and reverse engineering applications, making CMMs highly adaptable in industrial settings where accuracy, flexibility, and efficiency are critical (Artkin, 2022b).

The measuring accuracy of CMMs is affected by multiple error sources such as temperature, humidity, machine geometry, probing system performance, alignment strategy, measuring force (B. Wang, 2018). Coordinate Measuring Machines (CMMs) are widely recognized for their precision and versatility; however, they also present several disadvantages that limit their broader industrial application. The high cost of acquisition, installation, and maintenance which is driven by precision components, advanced software, and frequent calibration requirements makes them a considerable investment. Furthermore, CMMs are highly sensitive to environmental conditions such as temperature, vibration, and humidity, where even small variations can lead to measurement errors. In terms of operational efficiency, traditional CMMs are often slower than modern optical or non-contact measurement systems, particularly when dealing with complex geometries. Their limited portability also poses challenges for large or heavy components that cannot be easily transported to the measuring station. Skilled operation is another requirement, as programming, alignment, and data interpretation demand specialized metrology expertise, with improper setup potentially compromising measurement accuracy. Contact-based probing introduces additional drawbacks, including the risk of surface deformation or scratches on delicate materials, as well as distortion of thin or flexible parts under probing forces. Also, since CMMs require regular calibration and maintenance to ensure reliability, downtime and operational cost is increased. Many CMMs function offline and require dedicated setups, so they are not ideally suited for real-time production environments, they tend to create bottlenecks in high-volume manufacturing lines.

Coordinate Measuring Arms (CMAs), also referred to as Portable Coordinate Measuring Arms (PCMA), are portable metrological instruments designed to acquire three-dimensional (3D) measurement data of a workpiece. They work by tracking the spatial location of a probe tip attached to an articulated arm, relative to a fixed reference system built into the arm's structure.

Due to the absence of shifting units, they are not covered by the ISO 10360 norm quoted for CMMs (M. Kupiec, 2012). CMAs usually comprise of three to four mechanical links fused together by joints (usually six). The joints come equipped with angular encoders used for sensing angular rotation of the links. Combining the measured angles from the encoders and the length of the links, the measurement software can calculate the position of the probe at the end of the CMA using suitable kinematic equations (Andrzej & Adam, 2010) (Dupuis et al., 2017).

In most cases the joint of the arms are not actuated and need to be moved by an external force as seen on Figure 7A. In other cases the joints are fully actuated allowing the system to measure independently as seen on Figure 7(b) below.

(a)

(b)

Figure 7. (a). FARO's high-accuracy, 6 axis QuantumS Arm (Technologies, 2018). (b). Fringe projection system mounted on robot end effector (Luhmann, 2010).

When an operator touches the probe against points on a component's surface, the system records their exact 3D coordinates. By collecting multiple points, geometric features such as planes, cylinders, or angles can be reconstructed, enabling dimensional inspection, verification of geometric dimensioning and tolerancing (GD&T), and reverse engineering applications.

Unlike traditional CMMs, which are large, fixed, and highly precise, CMAs offer superior portability and flexibility. They allow measurement directly on the shop floor, close to the manufacturing process, thus reducing handling and setup time. However, this portability comes at the expense of lower accuracy and reliability, primarily due to manual operation and environmental variability. While in CMMs the probing process is controlled by automated sensors ensuring consistent force and positioning, in CMAs the operator plays a decisive role. Factors such as contact pressure (B. Wang, 2018), probe orientation, number and distribution of sampled points, and even operator skill can introduce variability into results. The measurement workflow of a CMA generally involves: Probing, Point acquisition, Feature reconstruction and Comparison/Analysis.

Studies, including the one presented by Cuesta et al. (2012), show that the reliability of CMAs is influenced not only by the device's specifications (probe size, arm accuracy, calibration conditions) but also heavily by the operator's technique and the type of feature being measured. For example, flatness or distance between planes can be measured with relatively low dispersion, while cylindricity or internal diameters present greater challenges due to the increased complexity of manual probing.

CMAs represent a powerful metrology tool where ease of use, flexibility, and portability are prioritized, but their accuracy depends on careful control of measurement parameters and operator training.

Light Detection and Ranging (LiDAR)

LiDAR technology has emerged as a powerful tool for achieving precise and accurate measurements across a wide range of applications, including surveying, mapping, urban planning, environmental monitoring, and the development of autonomous vehicles. (Ritik Rokade et al., 2017) (Pendse, 2024).

LiDAR works by emitting rapid pulses of laser light, often hundreds of thousands per secondtoward surrounding objects. When these pulses strike surfaces such as the ground, vegetation, or built structures, they are reflected to the sensor, enabling the collection of high-resolution three-dimensional data points that can be processed into detailed models of the scanned environment (Davis, 2012).

This process, repeated millions of times in different directions, generates a dense collection of data known as a point cloud, which captures the geometry and spatial distribution of objects with remarkable precision. Point cloud analysis has proven invaluable across disciplines, particularly in archaeology, where LiDAR has facilitated the discovery and documentation of previously undetected features, thereby enhancing interpretations of historical sites and landscapes (Syed, 2022).

Beyond archaeology, the resulting datasets support the creation of elevation models, forest inventories, surface reconstructions, and urban planning frameworks. In essence, LiDAR functions similarly to radar but relies on laser light, enabling high-resolution environmental mapping with far greater accuracy and detail.

LiDAR systems can be deployed on satellites, aircraft, or ground-based vehicles, allowing for flexibility in scale and resolution. Airborne and vehicle-mounted LiDAR, provide highly detailed, localized

measurements that are well-suited for infrastructure monitoring and autonomous navigation. Several types of LiDAR systems have been developed, including differential absorption LiDAR, giant aperture LiDAR, scanning hydrographic operational airborne survey LiDAR, CO_2 Doppler pulsed LiDAR, and toposys LiDAR systems (Kumar, 2018).

Each type offers distinct advantages and is tailored to specific applications. A key strength of LiDAR lies in its ability to overcome limitations inherent in traditional surveying methods, such as occlusion and sample sparsity, making it an increasingly preferred option in both geospatial sciences and autonomous vehicle technologies (Lin et al., 2021) .

Despite its significant advantages, LiDAR technology faces several challenges that limit its broader adoption (Z. Wang & Menenti, 2021). One of the primary issues is the high cost of acquisition and processing, which restricts access for many potential users. Additionally, the technology requires specialized expertise for data processing and interpretation, creating barriers for institutions lacking trained personnel. Data volume is another challenge as LiDAR generates massive point clouds that demand substantial storage capacity and computational resources for processing and analysis.

Another major challenge lies in technical and environmental limitations. LiDAR performance can be negatively affected by factors such as dense vegetation, adverse weather conditions, and surface reflectivity, which reduce accuracy and data completeness. Moreover, integrating LiDAR data with other remote sensing datasets remains complex due to differences in resolution, scale, and format.

Dynamic uncertainty can also be a major issue, it refers to the errors or variations in measurement accuracy that arise when either the LiDAR sensor, the target, or both are in motion. Unlike static uncertainty where measurements are taken of stationary objects from a fixed platform dynamic uncertainty account for additional factors introduced by movement, such as sensor vibration, platform velocity, scanning angle, and target motion. These influences can distort the timing, angle, or intensity of returned laser pulses, thereby affecting the accuracy of distance calculations and the reliability of the resulting point cloud.

3.3 Comparative Analysis of Metrology Technology

Choosing the appropriate metrology solution requires careful consideration of multiple factors, including accuracy, measurement range, repeatability, cost, mobility etc. While certain techniques may demonstrate clear advantages in specific metrics, no single method is universally superior across all applications. Therefore, a comparative analysis is essential prior to selecting the most suitable option. To ensure a fair evaluation, it is often recommended to apply different measurement methods to the same object, allowing for a comprehensive comparison of performance and reliability under identical conditions.

Matache et al. (2015), conducted the measurement of a small size gas turbines using a CMM (DEA DELTA CMM) and a 3D Scanning (Artec™ 3D white light scanner) solution. A major difference observed in the two solutions is their physical limitations.

For concave dihedral intersections, the coordinates may occasionally be challenging or even impossible to read because the CMM is typically limited by both the probe's tip and its shape. The 3D Scanner is superior in this regard, as it can scan the entire blade without making any major errors. As 3D scanning supports high degree of Automation, the time needed to capture surface data is significantly reduced. A comprehensive analysis of the results concludes that the 3D scanner measurements were most accurate in the leading-edge region of the blade, reaching a margin of 0.25 mm, higher errors (between 0.3-0.48 mm) were noticed on the rest of the blade. The results from the CMM measurement were however generally closer to the CAD model compared to those from 3D Scanning.

The advantages of the 3D Scanner over the CMM can be summarised as:

- Ease of Use: Shorter scanning time and lower skill requirements for the operator (Altinisik & Bolova, 2021).
- Comprehensive Data Acquisition. Unlike the CMM, the 3D scanner was able to capture the entire trailing edge geometry
- Higher Point Density: The greater number of acquired surface points statistically results in a more accurate representation of the scanned object.

- Reduced Workload: Scanning with a 3D Scanner requires significantly less time and effort compared to CMM inspection.
- Portability and Cost: The 3D Scanner is more portable and generally less expensive than CMM equipment. Additionally, advanced post-processing software enhances its utility.

Although both measurement solutions are okay for typical quality inspection, the CMM does have an accuracy advantage over the 3D scanner (Matache et al., 2015).

CMMs and Laser Trackers are both widely used in precision metrology, but they differ significantly in performance characteristics and applications. CMMs offer extremely high accuracy at the micron level (typically ±1 to 5 μm), making them ideal for precision inspection of small to medium-sized components such as aerospace, automotive, medical, and tooling parts. However, their measurement range is limited to the machine volume, usually less than 2 to 3 m^3 for standard models, and they are fixed systems requiring components to be brought to the machine, which restricts portability. They are also relatively slow when measuring large or complex geometries but excel at detailed GD&T analysis, calibration, and CAD comparison. On the other hand, Laser Trackers provide slightly lower accuracy (typically ±10 to 50 μm. Over large distances) but compensate with a very large measurement range, often extending up to 80 to160 m in radius, which makes them suitable for large-scale applications such as aerospace fuselage inspection, wind turbine and ship building, and real time assembly alignment. They are highly portable and can be deployed directly on the shop floor or in the field, offering faster measurement speeds for large assemblies and alignment tasks. Both systems are costly, though CMMs carry higher maintenance demands, while Laser Trackers are more cost effective for large scale tasks. CMMs require controlled environments free from temperature fluctuations and vibrations to maintain accuracy, whereas Laser Trackers are more adaptable to workshop conditions but remain sensitive to line-of-sight obstructions, dust, and reflective surfaces.

The selection between laser trackers and photogrammetry systems is largely determined by factors such as measurement range and accuracy. Laser trackers are particularly well suited for long range applications, as they are capable of measuring distances with high precision over several meters. For example, the AT960 from Hexagon Metrology achieves an accuracy of approximately 15 μm at a 2 m distance and around 500 μm at 80 m, demonstrating both precision and scalability over extended ranges. More recent models, such as the AT500, further enhance performance with a measurement range of up to 160 m and the integration of a built-in controller and power system, thereby improving the overall portability and usability of the system.

While photogrammetry can achieve high accuracy for close-range objects, its range/accuracy is typically limited compared to laser trackers. This limitation is due to the reliance on capturing clear and detailed images, which may be challenging for objects located far away. Although an argument can be made for the volume of data captured, while photogrammetry captures large amount of data with lower accuracy, Laser trackers have the advantage of being able to directly measure the position of a target point by reflecting a laser beam off a retroreflective target placed on the object. This direct measurement method eliminates the need for complex image processing algorithms and the uncertainties associated with them (Bierlich et al., 2021), making laser trackers more efficient for high accuracy high range applications and photogrammetry better for lower accuracy high volume applications. An accuracy/range comparison between the different types of metrology equipment is seen on Figure 8.

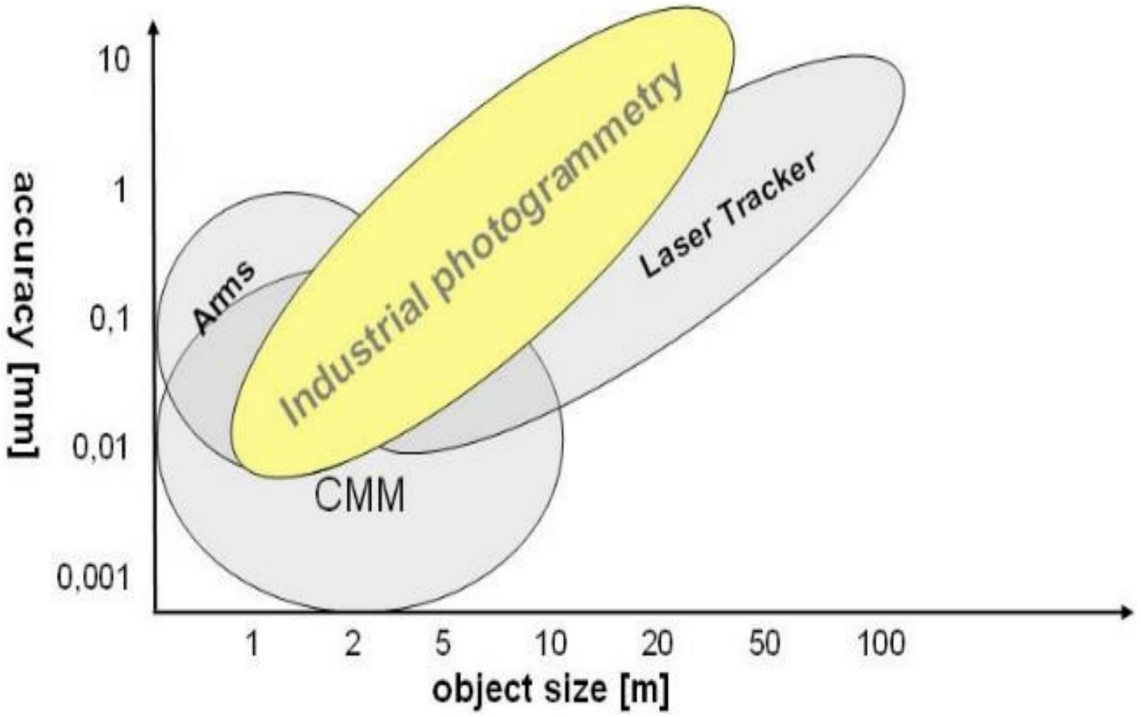


Figure 8. Size and Accuracy comparison of measurement systems (Bösemann, 2016)

Recent studies have highlighted the potential of combining laser trackers and photogrammetry to achieve improved measurement outcomes. For instance, Velios & Harrison (2010), demonstrated this approach in capturing 3D models of a mosque, showing that the integration of both methods provided sufficient data for the accurate reconstruction of the structure.

Koch & Kaehler (2009), demonstrated that by combining photogrammetry and laser scanning, the strengths of both techniques can be effectively capitalized upon. Their case study showed that fine details, which were difficult to capture from noisy point cloud scans, could be more accurately extracted from images. However, sparsely structured surfaces posed challenges for near-range photogrammetry, as achieving sufficient point cloud density was difficult. By integrating photogrammetry with laser scanning, both high-density point clouds and fine detail capture were achieved, resulting in a more comprehensive and accurate measurement dataset.

Although most applications combining photogrammetry and laser scanning fall under architectural (Kadobayashi et al., 2004) and archaeological (Ioannidis & Tsakiri, 2003) (Beraldin, 2004) application, it might be seen to play a more dominant role in manufacturing in the future.

Table 2 provides the comparative analysis of the various metrology solutions discussed above.

Technology	Laser Tracker	Photogrammetry	Coordinate Measuring Machines (CMM)	Coordinate Measuring Arms (CMA)	Electromagnetic Distance Measurement (EDM)	LiDAR
Working Principle	Uses a laser beam reflected from a target to measure distance and angle precisely	Uses overlapping images and triangulation to determine 3D coordinates	Contact probe physically touches object to record 3D coordinates	Articulated arm with a probe for manual or laser scanning measurements	Uses phase shift or time-of-flight of electromagnetic waves to calculate distance	Emits laser pulses and measures return time to build dense 3D point clouds
Accuracy	Very high (microns to sub-mm)	Moderate (mm,cm scale)	Extremely high (micron level)	High (tens of microns)	Moderate to high (mm,cm scale)	High (cm to mm depending on system)
Range	Up to 80 m	Very large (hundreds of meters to kilometers)	Limited to machine size (typically <3 m)	Limited reach (1–5 m depending on arm size)	Long (several km in surveying instruments)	Short to very long (meters to several km, airborne/satellite)
Portability	Portable (requires setup)	Highly portable (camera-based)	Not portable (fixed installation)	Portable but limited range	Portable (used in total stations)	Portable (ground, drone, airborne, satellite)
Applications	Large part inspection, aerospace assembly, industrial alignment	Architecture, surveying, cultural heritage, deformation monitoring	Precision manufacturing, part verification, quality control	On-site inspection, automotive, aerospace parts	Land surveying, construction, geodesy	Topographic mapping, forestry, urban planning, autonomous vehicles
Limitations	Sensitive to line-of-sight issues, expensive	Lower accuracy than laser methods, lighting conditions affect results	Expensive, slow, limited to controlled environments	Operator-dependent accuracy, restricted working volume	Requires clear line of sight, accuracy drops over long distances	Performance reduced by vegetation, weather, and surface reflectivity
Primary Data Output	Outputs high-accuracy 3D coordinates (X, Y, Z), along with distance and angular data relative to a reference target.	Generates 3D coordinates (X, Y, Z) from 2D images, producing point clouds, models, or CAD-compatible data.	Provides 3D coordinates (X, Y, Z) with geometric features, dimensions, GD&T evaluations, and CAD comparisons.	Similar to CMMs but a Portable system providing 3D coordinates (X, Y, Z) and point clouds for alignment, inspection, and reverse engineering.	Outputs distance and angular data, which can be combined to generate 3D coordinates.	Generates dense 3D point clouds for mapping, modeling, and object reconstruction.

Table 2. Technology Metrics and comparative table of various metrology technologies

The high cost of advanced metrology devices, such as laser trackers and coordinate measuring machines (CMMs), remains a significant barrier to widespread adoption, particularly among small- and medium-sized enterprises (SMEs) and in resource-constrained regions. Initial investments frequently exceed £40,000, with additional expenses for maintenance, calibration, and operator training further increasing the financial burden. The challenge is compounded by the rapid pace of technological obsolescence, which necessitates frequent upgrades to remain competitive. As a result, many SMEs are compelled to rely on less precise alternatives, potentially compromising product quality and consistency. Addressing these barriers requires the development of more cost-effective approaches, such as hybrid metrology systems or subscription-based service models, which can reduce upfront costs and broaden accessibility.

4. Concepts in Modern Metrology

4.1 Precision Engineering in modern industries

The increasing emphasis on measurement accuracy and reliability has driven significant advancements in precision engineering, which in turn has transformed the metrology sector. Central to this progress is the pursuit of ever-greater accuracy striving for the next decimal place to ensure that the dimensions of machine components conform as closely as possible to their nominal values.

Advances in manufacturing processes have led to greater precision and productivity, enabling industries to achieve higher levels of quality control while also enhancing the reliability and credibility of scientific research outcomes (M. Liu & Luo, 2014).

In aerospace and medical engineering, both engineers and end-users increasingly rely on product performance enabled by precision engineering. Advanced measurement tools such as coordinate measuring machines (CMMs) and laser scanning systems now make it possible to capture highly accurate measurements of complex surfaces and geometries, ensuring greater reliability and quality in published results (Nekrasov et al., 2018). It has also contributed to the development of more accurate calibration methods, which are essential for ensuring measurement traceability. While precision engineering holds significant promise, its practical application remains challenging, as it places stringent performance demands on both measurement equipment and metrology engineers.

4.2 Digital Metrology and Tools

By employing advanced technologies such as laser scanning and intelligent probes, digital metrology tools enable precise measurement of dimensions, shapes, and other physical properties. These tools have become indispensable in nearly all major manufacturing companies, particularly during the research and development (R&D) stage of product design. In addition, they play a critical role in day-to-day operations, supporting the quality inspection of manufactured parts. Their value is especially evident in industries such as aerospace, where the accurate measurement of large and complex components is essential (Merghache & Ghernaout, 2014). A digital metrology system can range from a simple standalone device, such as a digital micrometre, to highly sophisticated instruments like laser trackers, photogrammetry systems, articulated arms, or coordinate measuring machines (CMMs), which operate in conjunction with specialized software interfaces. Software platforms such as Spatial Analyzer, PolyWorks, Verisurf, Quick Surface, TouchDMIS, Modus, MCosmos, Metrosoft Quartis, Metrolog X4, and Arcocad, among others, provide dedicated plugins and interfaces for integration with a wide range of metrology equipment. A brief investigation reveal that the various software has different merits and demerits.

Commonly supported CAD formats include Catia V4 and V5, STEP, and IGES, with most metrology software also accommodating STL, SolidWorks, and Autodesk Inventor files. Verisurf and PolyWorks offer broader compatibility with hardware devices, with PolyWorks providing plugins for a wide range of point cloud capture systems and single-point measurement devices.

Most metrology software supports 3D dimensional analysis and inspection, generally following a similar workflow across platforms. This typically involves scanning machine parts and comparing the resulting data to the original CAD model. Additionally, PolyWorks, Spatial Analyzer (SA), Metrolog X4, and Verisurf support the creation of Model-Based Definitions (MBD). PolyWorks further

distinguishes itself with a communication suite that streamlines error reporting, thereby accelerating the detection and correction of inspection-related issues.
With a proven track record in managing large-scale projects, PolyWorks, Verisurf, Metrolog X4, and SA are widely adopted across the aerospace and automotive industries.

4.3 Metrology and Digital Twin

A digital twin is a virtual representation of a physical object, system, or process, designed to mirror and support its real-world counterpart. Created using data collected from the physical entity, digital twins typically exist within a digital environment (Wright & Davidson, 2024) and serve as powerful tools for simulation and data generation (Baer et al., 2022). They are developed with the aim of enabling safer, more efficient experimentation and optimization, helping to reduce costs, minimize risks, and manage the complexity associated with physical operations.
For digital twins to operate effectively, they require continuous, up-to-date data from sensors that monitor the state of their physical counterparts (Z. Wang, 2020). This real-time synchronization ensures that the digital model accurately reflects changes in the physical system. In theory, with the right network of sensors, a near-perfect digital twin could be created. However, this remains challenging as many industries still rely on passive devices, which were sufficient during the third industrial revolution when manufacturing heavily depended on human intervention. With the emergence of Industry 4.0 and the anticipated transition to Industry 5.0 (Sharma & Singh, 2020), there is an increasing need for manufacturing systems to become smarter, more connected, and fully integrated into digital ecosystems.
Digital twin technology is highly versatile and enables complex applications in automated metrology. Lindqvist et al. (2023), demonstrated this at Saab Aeronautics by developing a simulation-based process for programming and designing an automated laser radar system. This approach defined the dimensional metrology sequence and created a computer-simulated environment where a laser radar measurement sensor was virtually modelled and integrated with associated programming tools. To achieve this, existing offline programming software was enhanced with new functionalities, including a reliable digital twin model continuously updated with sensor data from the physical system.
Digital twin technology can also be applied to highly complex systems. Ecke (2018), demonstrated its potential in assessing spacecraft reusability after re-entry. To evaluate strain and temperature distributions on a frame component of the X-38 prototype emergency crew return vehicle for the International Space Station, an optical fibre Bragg grating measurement device was developed. The sensors, interfaces, and opto-electronic components were specifically adapted for vacuum and space applications and tested for compliance with operational requirements. During launch and re-entry, eight fibre Bragg gratings were employed for strain measurements and four for temperature monitoring, enabling real-time assessment of mechanical and thermal loads on the spacecraft's structural elements. The resulting data informed decisions on the vehicle's reusability for subsequent missions, supporting efforts to reduce operational costs.
To address the limitations created by blind spots and data transfer errors associated with traditional LiDAR-based assembly technology. Zhao et al. (2020), proposed to combine an optical fibre sensor network with digital twin technology, which will allow test data from the assembly entity state in the real world to be applied to the "twin" model in the virtual world. The system diagram is shown on Figure 9.

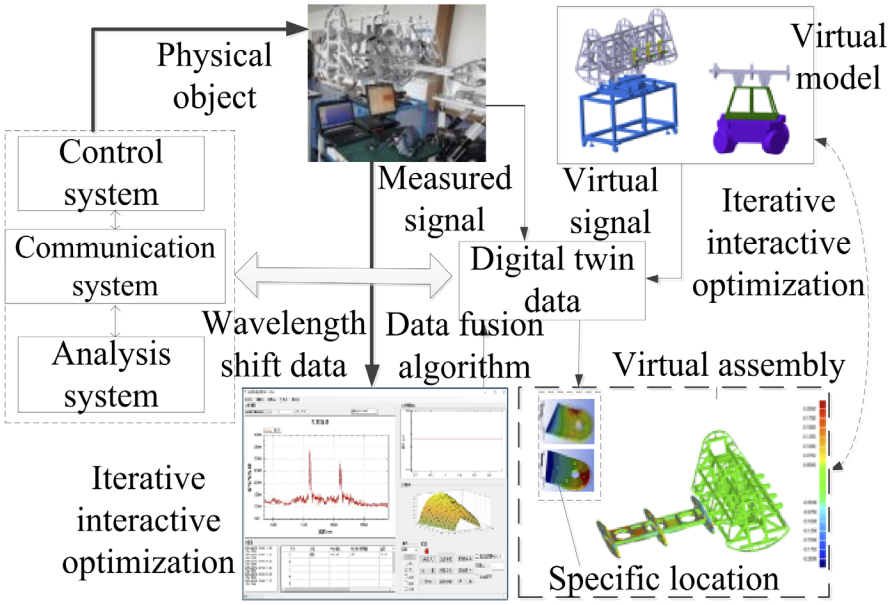


Figure 9. Optical fibre sensing intelligent assembly system based on digital twin model (Zhao et al., 2020).

An assembly state monitoring system was designed based on the optical fibre sensor network, and an assembly state monitoring algorithm was proposed. The result of the experiment, which simulated the building of a massive structure, demonstrated that visual calibration can reduce test error to a narrow range. Statistics reveal that for normal surfaces, the average measurement accuracy error is better than 11.2%, while for irregular surfaces, it is better than 14.8% and the average position deviation accuracy during modelling of large-scale structure assembly trials is 0.043 mm.

From the applications discussed above, it is evident that metrology and digital twin technologies are likely to become increasingly integrated in the future. As these fields converge, new hybrid solutions may emerge, with metrology software progressively incorporating digital twin capabilities to enhance accuracy, efficiency, and decision-making.

5. Application of Metrology in Manufacturing

Metrology has become a cornerstone of modern manufacturing, functioning both as a guarantor of quality and a catalyst for innovation. As (Kehinde et al., 2024) highlight, measurement science plays a critical role in ensuring dimensional accuracy, maintaining surface integrity, and meeting rigorous industry standards (Fan & Kinnell, 2021). The evolution of metrology from traditional mechanical tools to advanced technologies like coordinate measuring machines (CMMs), optical metrology, and 3D scanning demonstrates how manufacturing has been transformed into a data-driven, quality-focused ecosystem.

Metrology finds applications across a wide range of industries. In automotive and aerospace manufacturing, it safeguards the precision and safety of complex components; in electronics, it underpins micro-scale quality control for semiconductors and circuit boards; and in the medical sector, it ensures regulatory compliance while protecting patient safety. Across these domains, the integration of real-time monitoring and feedback loops has strengthened reliability, minimized waste, and facilitated the production of intricate components with exceptionally tight tolerances.

In manufacturing, the importance of metrology in measurement-assisted assembly cannot be overstated (Muelaner, 2010). Once confined to a traditional quality control role, metrology has now become an integral element of the manufacturing process itself (Maropoulos et al., 2014). Emerging strategies such as part-to-part and jiggles assembly are gaining traction (Muelaner et al., 2011), particularly in aerospace manufacturing, a sector that has historically depended on jigs and tooling.

Due to large parts and complex geometry, it is a challenging task to automate the manufacturing process in structures like ships (Maisano et al., 2023) and airplanes. But of recent, several research have combined metrology solutions with other assembly processes to achieve impressive results. Using the FA^{3}D system, Drouot et al. (2018), aimed to convert the assembly line to an assembly cell. By integrating industrial robots with high-precision metrology solutions, aircraft assembly processes have achieved significantly improved component positioning accuracy and reduced rework, attaining positional tolerances within ±0.1 mm.

It is also used in metrology enabled automation and for product inspection and life monitoring. (Muelaner et al., 2009). Ensuring that tight tolerance is met, and that high quality fit is achieved and maintained.

In structural engineering, metrology plays a critical role in monitoring and compensating for structural deformation. While electronic distance measurement (EDM) systems are commonly applied in residential construction, more sensitive projects such as particle accelerator facilities demand higher levels of precision. In such cases, laser trackers are employed for their superior accuracy, as demonstrated in the alignment of complex tunnel networks for high-energy physics experiments.

Next-generation aircraft demand heightened performance standards, which in turn impose stricter quality requirements on both design and manufacturing. For certain components, machining deformation tolerances are specified at within 0.05 mm/m, a remarkably tight margin that presents significant challenges for current manufacturing capabilities (Zhao et al., 2021).

As part of the *DIGIMAN* project, a novel optical measurement method was developed to evaluate sheet metal components for shape accuracy and strain distribution. Using photogrammetry, the technique identifies deviations caused by spring-back based on the component's geometric properties, while also enabling strain analysis at critical stamping locations (Boesemann, 2000). Minimizing spring-back requires uniform stress and strain distribution during forming; in this case, it was mitigated by improving material flow between the blank holder and the die.

To determine the strain of warped square grids whose detection is simpler to automate using photogrammetry, a technique known as the "modified tangent method" was used. The principal strains were identified using the calculation of angles and distances in an arbitrary three-dimensional space. Using springback analysis and Visio plasticity, the system can identify crucial strain distributions that deviate from the ideal geometry.

These applications demonstrate what can be achieved and have inspired industries to raise their standards. Figure 10 shows how tolerance expectations in automotive manufacturing has evolved.

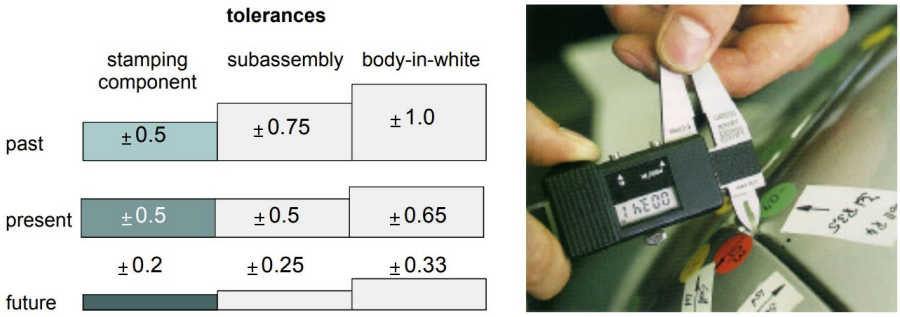


Figure 10. Increasing Tolerance in automotive manufacturing (Boesemann, 2000)

Metrology serves as a correction tool to the various factors (self-weight, assembly stress and other forces) that cause deformation in large-scale manufacturing. In some cases, multiple laser trackers are used to determine the position and orientation of large structures like aircraft wings in space (Chen et al., 2018). This usually involve placing targets devices like SMRs around the assembly cell and measuring their position. An example is seen on Figure 11.

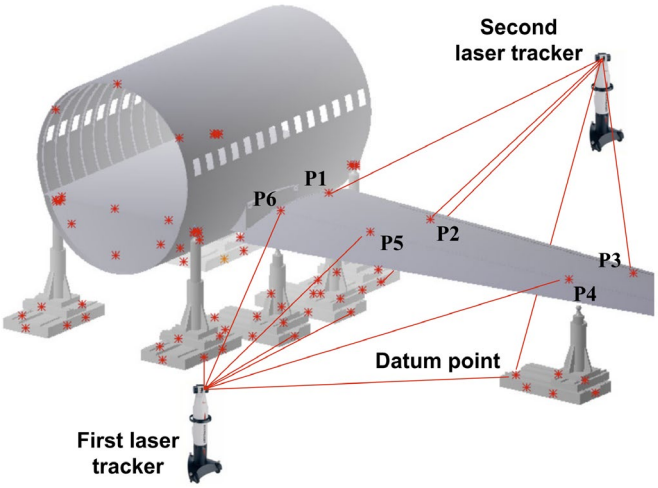


Figure 11. The alignment of a wing and a fuselage using Laser trackers and reflectors (Chen et al., 2018)

In many intelligent automation systems, especially as pertains to aircraft assembly, metrology systems are also used to obtain position differential of objects in an assembly cell, making it easier to obtain six degrees of freedom (6DOF) data used to guide robotic systems. This has made automation of both inspection (Cioboată et al., 2021) and assembly processes possible.

As of the time of publication, metrology has seen its way in welding (Boldsaikhan et al., 2023), construction, medicine (Karaböce et al., 2020), art (Ceren Altin & Ipek Ozil, 2008), even agriculture (Chirico & Bonavolontà, 2020) and will most likely become more prominent in the future.

6. Future of Metrology

Over the years, metrology equipment has undergone significant improvements, with further advancements expected in the future. Key players in dimensional metrology include Hexagon, Jenoptik, Nikon, Danish Micro Engineering, Renishaw, Carmar Accuracy, Applied Materials, GOM, Carl Zeiss, and FARO Technologies. As technology progresses, some of these companies will grow by leading innovation, while others may struggle to adapt. Since the underlying technologies that form the basis of metrology systems are continuously evolving, it follows that the equipment itself will also advance.

Laser trackers exemplify this evolution. Their combination of high-precision interferometers for accuracy and absolute distance meters (ADMs) for real-time target tracking has made them indispensable. Recent innovations, such as Hexagon's AT500, demonstrate that substantial improvements in laser tracker technology remain possible.

Photogrammetry is another area poised for rapid development. The increasing availability of mobile 3D scanning applications such as Kiri Engine, Widar, Polycam 3D Scanner, Magiscan, and Arloopa, highlights how smartphone cameras can now generate polygonal meshes or point-cloud data (Cheryl Vaughn, 2023). While these tools are not yet suitable for industrial applications, advances in image processing could eventually deliver sufficient accuracy to challenge traditional laser scanners and photogrammetry kits, much like phone cameras have displaced standalone cameras.

Progress in microelectronics continues to enhance metrology, while traditional analogue devices are becoming more sophisticated through the addition of new features. A notable example is API's Active Target SMR (Figure 12), which incorporates motorization technology that automatically aligns the SMR to the laser tracker source regardless of positional changes. This innovation simplifies the measurement of moving targets and represents the type of transformative improvements shaping the future of metrology.

Figure 12. API's active target SMR (API Metrology, 2023).

Some areas that can be improved include:

Accuracy and Repeatability: Constant advancements in sensor technology (Interferometers) and calibration methods may result in even greater measurement accuracy. This can open up new uses and applications for laser trackers beyond current fields of applications.

Integration with AI and Robotics:
Cesare Alippi et al. (1998), concluded that the application of AI techniques in measurement brings about a new set of challenges relating to the characterization of novel instrumentation and measurement methods and that more research is required to develop appropriate methodologies to determine the accuracy, precision, and reliability of measurements made using advanced instrumentation and measurement methods. This is particularly important regarding the algorithmic choices embedded in the software and computing systems.
Several research going on in metrology has measurement equipment integrated with robotic and artificial intelligence systems. In the future, this could become a dominant practice with companies providing fully integrated solutions. This will have the possibility to automate measurement procedures, boost productivity, and lower the possibility of human error. Decision-making and data analysis in real time may be made possible by this connection.
A Pilot Study by Kucharski et al. (2024), presents a novel approach to supporting decision-making in surface metrology through machine learning. The authors developed an algorithm trained on over several measurements from both tactile and non-tactile systems, using parameters such as surface material, filtering, and roughness indicators with their uncertainties. By applying models like Random Forest, CART, KNN, and GBM, the study achieved up to 98.6% accuracy in predicting the appropriate measurement technique, with Random Forest emerging as the most effective method. This highlights the potential of ML to automate the preliminary selection of metrology systems, reduce operator workload, and improve measurement reliability.
Other researchers like Tameem Adel et al. (2024), take a different approach, where metrology is used to enhance AI, rather than AI being employed to improve metrology.
There is also the fear that introducing AI systems to metrology will eventually make humans/operators redundant or less skilled (R. Taymanov et al., 2022). Either way, the concept of AI will play important roles in the future of metrology software.

Accuracy and Repeatability: Continuous advancements in metrology technologies have significantly improved both accuracy and repeatability, thereby broadening their applications in modern manufacturing. In laser trackers, innovations in interferometer design, absolute distance meters (ADMs), and advanced calibration algorithms have enhanced sub-millimetre accuracy and repeatability, enabling precise alignment in aerospace, automotive, and large-scale assembly operations. Photogrammetry has benefited from improved camera resolution, image processing algorithms, and computational power, which have increased the accuracy of 3D reconstruction and reduced errors in shape analysis and strain measurement, making it increasingly viable for industrial inspection and quality assurance. Similarly, advances in coordinate measuring machines (CMMs), including probe technology, thermal compensa-

tion, and machine kinematics, have yielded higher accuracy and faster measurement cycles, with modern CMMs achieving nanometre-level repeatability for complex geometries and freeform surfaces. Electronic distance measurement (EDM) systems have also improved through the integration of laser-based methods and digital signal processing, delivering greater distance accuracy and stability for applications such as construction and structural monitoring, where repeatability is vital for long-term deformation tracking. Collectively, these advancements enhance process reliability, enable tighter tolerances, and support the growing demand for zero-defect manufacturing.

Augmented and Virtual Reality (AR and VR) Integration: Although the origins of AR/VR can be traced back to the 1950s, recent consumer products such as Apple's Vision Pro have introduced these technologies to a broader audience. In the future, metrology software could be seamlessly integrated with AR devices, transforming the way measurements are performed and visualized. Deviations could be displayed in real time as overlays on the measured object, allowing observers to pinpoint errors with precision. Similarly, uncertainty clouds could be visualized around the measured SMR, offering an intuitive representation of measurement reliability. Such advancements would not only enhance accuracy but also enable faster, more efficient, and more user-friendly inspection and assembly processes.

Increased Range: Another key performance metric of a metrology system is its measurement range. Future developments are likely to enable systems to capture targets at much greater distances while maintaining high accuracy. Photogrammetry already offers long-range measurement capabilities, albeit with lower precision. However, advances in camera zoom, sensor quality, and image-processing algorithms could significantly improve the accuracy of data extracted from distant objects. Similarly, next-generation laser trackers equipped with more powerful lasers may extend interferometer beam travel without significant energy loss. These innovations point toward a future where metrology systems combine long-range capability with unprecedented accuracy.

Cost Reduction: As metrology technologies gain wider adoption across industries due to their ease of use and broad applicability, economies of scale may drive down equipment costs. This trend could make high-quality metrology more accessible to a wider range of sectors and regions. Currently, many countries remain excluded from using state-of-the-art systems, as their high cost is prohibitive for weaker economies, limiting industrial growth in those areas. However, promising developments in smaller, more affordable metrology devices offer hope. For instance, the Faro Orbis scanner provides versatile functionality at a relatively lower cost, while the HandySCAN 3D from Creaform serves as a practical alternative to higher-end systems such as the T-Scan 5. As technology costs continue to decrease over time, advanced metrology equipment is likely to become more affordable, enabling previously excluded regions to participate more fully in manufacturing innovation and global competition.

Wireless Connectivity: Integration of wireless communication capabilities could enable easier data transfer and remote monitoring, allowing users to control and analyse measurements from a distance. This feature is already seen in the AT500 Laser tracker and a host of other wireless devices.

Overall, the future of metrology seems promising, with continued innovation driving improvements in accuracy, portability, automation, and integration with other technologies. These advancements have the potential to revolutionise various industries, from manufacturing and construction to aerospace and automotive.

The future of metrology demands a concerted focus on advancing technologies to address the multifaceted challenges of modern manufacturing and quality assurance. Research must prioritise the integration of AI to automate measurement processes, enhance anomaly detection, and develop adaptive calibration systems that minimise operator dependency. Equally critical is the exploration of AR/VR technologies, enabling real-time visualization of measurement deviations, immersive training environments, and remote collaboration for enhanced efficiency. Efforts to democratise metrology through cost-effective solutions, such as hybrid measurement devices, shared resource platforms, and

decentralised data processing systems, are essential to support small-scale industries and resource-constrained regions. Furthermore, the establishment of universal data exchange protocols and blockchain frameworks can ensure secure, standardised, and interoperable measurement data in Industry 4.0 ecosystems.

Looking forward, the future of metrology lies in harnessing emerging technologies. Artificial intelligence, machine learning, and the Internet of Things are expected to enable predictive maintenance, autonomous quality control, and closed-loop manufacturing. Further advances in nanoscale and quantum sensing, along with integration into Industry 4.0 frameworks, promise to expand metrology's scope and influence.

7. Conclusion

Metrology, the science of measurement, has evolved to meet the precise demands of modern industries such as aerospace, automotive, and large-scale manufacturing. The shift from manual instruments like rulers and calipers to advanced systems such as laser trackers, photogrammetry, and CMM highlights the advancements made to ensure measurement accuracy, reliability, and efficiency. These technologies are now integral to every phase of product development, from design to manufacturing and quality assurance.

This paper's comparative analysis of key metrology technologies has provided insights into their unique strengths and limitations. Laser trackers offer high precision over large distances, making them invaluable for applications such as aircraft assembly and tunnel construction. Photogrammetry provides flexibility for medium-range, high-detail 3D modeling, although its accuracy decreases at longer ranges. CMMs and CMAs excel in tasks requiring extremely tight tolerances, critical for precision manufacturing, although these systems can be costly and limited in mobility.

The potential of future advancements in metrology is also significant, particularly with the integration of digital tools such as artificial intelligence, digital twins, and advanced sensor technologies. These innovations will shift metrology from simple measurement tools to more dynamic systems that enhance real-time monitoring, predictive maintenance, and automated decision-making in production processes. The rise of digital twins, in particular, allows manufacturers to simulate and optimise processes in real-time, leading to improved accuracy and efficiency in manufacturing.

Artificial intelligence is poised to further revolutionise metrology, offering automation of complex tasks, reducing human error, and improving data analysis. AI-driven systems can interpret data faster, detect inconsistencies, and adjust processes in real time, which will support intelligent and automated manufacturing. As industries adopt these advanced systems, the role of metrology will evolve, contributing to smarter, more efficient production environments.

Challenges remain, particularly in terms of cost and accessibility. Technologies like laser trackers and CMMs, while essential for high-precision applications, are expensive and require specialised operators and controlled environments. Expanding the accessibility of these technologies through cost-reduction strategies and technological innovations will be crucial for widespread adoption across industries.

Metrology remains a cornerstone in ensuring that products meet the highest standards of quality, precision, and reliability. As these technologies continue to evolve and integrate with AI and digital systems, metrology will not only support but also drive further advancements in industrial processes, optimizing production, reducing waste, and improving product quality.

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2026-12-31
Taylor & Francis
https://doi.org/10.1080/0951192x.2025.2599551
Izuwa E, Asif S, Webb P. (2025) Evolution and application of dimensional metrology: a comparative review. International Journal of Computer Integrated Manufacturing, Available online 28 December 2025

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