MĀPAN-Journal of Metrology Society of India (March 2019) 34(1):97–104
https://doi.org/10.1007/s12647-018-0291-3

ORIGINAL PAPER

Relevance of Dimensional Metrology in Manufacturing Industries

G. Moona*, M. Jewariya and R. Sharma

CSIR-National Physical Laboratory, Dr. K. S. Krishnan Marg, New Delhi 110012, India

Received: 10 July 2018 / Accepted: 09 October 2018 / Published online: 25 October 2018

Abstract: Measurement is the most fundamental concept of science and technology that leads to innovations. As per the general concept, measurement is just a tool to determine quantity, whereas in reality, measurement is a fundamental aspect to control and improve various parameters associated with different technical affairs. In the present scenario, the manufacturing of extremely complexed products needs high quality control to meet the design specifications, desired functional outcomes and norm compliances. In industrial manufacturing, the main objective is quality control by eliminating errors and improving the process by precision dimensional measurement methods/devices and following standards and recommended guidelines. Precision and traceable dimensional metrology caters the industry needs ranging from macro-engineering applications to nanotechnology and helps in supporting the objective "make it right in the first time" and hence has become an inextricable part of the advance manufacturing industry.

Keywords: Measurement; Precision; Nanometrology; Traceability; Uncertainty; Standards

1. Introduction

"One accurate measurement is worth a thousand expert opinions", said Grace Murray Hopper. In our daily lives, we often encounter a long list of activities or items with common basis "measurement". Even then, common man is not aware of the fact that how important is measurement to one's life? and how does it help to make choices and decisions?

Measurement is involved in every aspect of our daily life and supports societal well-being in the following ways:

- Ensuring fair trade.
- Ensuring quality control in manufacturing.
- Controlling effectiveness of healthcare measurement devices.
- Ensuring consistency in international time standards for smooth communication and navigation.
- Controlling emissions of harmful gases and noise level.
- Utilizing measurement for defence applications and security threats.

It has been experienced that, in scientific and engineering fields, precise and accurate measurements are of preponderant significance. The need of accurate measurements in engineering was realized way back in 1847. Later in twenty-first century, most of the industries started relying upon precision measurements; specifically, dimensional metrology had to be in pace with manufacturing industry's ever-increasing advance requirements [1]. The most important role of dimensional metrology is to maintain primary standard of length for realization of SI unit "metre" and to provide traceable measurements on national/international level. In manufacturing, there are many critical aspects where precision measurement becomes essential, such as measurement of customer rejection/returns due to bad-quality or out-of-specification products, measurement of total time taken in whole process, measurement of time taken in changing set-ups, measurement of specified dimensions, measurement of average number of units being produced, measurement of utilization of manufacturing capacity and measurement of overall equipment effectiveness to save cost and time [2]. Here, it is extremely important to first understand the design intent, manufacturing processes and inspection processes. Quality control actually depends upon the reliable information about characteristics and process control of the product, and quality assurance is defined as the compliance with designed specifications, expected outputs and customer satisfaction. In manufacturing, this information can be obtained by authentic and real time dynamic dimensional measurements in extreme working

*Corresponding author, E-mail: moonag@nplindia.org

environment; hence, precise dimensional metrology supports the manufacturing of components for strict adherence with desired design specifications and functional requirements.

2. Dimensional Metrology in Manufacturing: State of Art

Measurement plays a vital role in every aspect of societal life. It is a proven fact that simple measurement mistakes in science and technology can cause awful consequences. The entire life cycle of a product is underpinned by accurate and precise dimensional measurements and associated procedures.

2.1. Implications of Precise Dimensional Measurements

In manufacturing, the idea of standardizing parts, parameters and industrial processes is of prime importance. Currently, 75% of the components used by any manufacturer are produced by other industries; thus, it becomes essential for the manufacturer to inform the subcontractors about acceptance criteria in terms of dimensional/electrical/chemical/thermal characteristics to avoid rejections. Even a diminished negligence in dimensional measurements can cause catastrophic consequences in case of automobile and avionics industry, affecting the engine efficiency, flight speed and controlling fuel consumption. In aerospace sector, the accurate measurement of in-service wear of turbine blades in terms of different blade features like blade height, throat area, leading edge, trailing edge and cooling holes using coordinate measuring machine becomes extremely critical to troubleshoot the potential safety issues. Leading automobile manufacturers consider the facilities and resources for effective dimensional measurements at design stage, and later the analysis of measurement data is integrated with the production system, so that the real time changes can be made whenever required. In addition to the above sectors, renewable energy sector also depends largely upon precise dimensional measurements in order to check the quality and efficiency of such technologies and associated systems. By using advance dimensional metrology techniques, better wind turbines can be designed and manufactured to cater the constantly increasing need of energy by replacing the conventional energy arrangements by renewable sources. Precise dimensional measurements also play important role in manufacturing of advance robots. For example, robots with imaging techniques are manufactured to monitor the condition of harvestable crops, in order to improve the productivity of farmers. Studies done in past years have predicted that precise dimensional metrology shall significantly evolve in future to underpin manufacturing industries by providing tighter tolerances to products for desired functioning, covering a huge range of component sizes (from MEMS to aircraft wings), addressing the key economic issue by faster detection of malfunctioned parts, developing interchangeable cost-effective technical solutions, giving appropriate attention to thermal behaviour of real components and catering the manufacturing of complexed parts for higher function integrations [3].

Precise dimensional measurements in manufacturing help in:

- Ensuring quality
- Reducing waste
- Using new techniques and materials
- Increasing productivity
- Higher profits
- Increased customer satisfaction

2.2. Existence of Dimensional Metrology in Industrial Arena

In manufacturing, precision dimensional metrology comes into picture in the form of inspection, which means checking of materials/products and comparing them with some established standards. Inspection of different components has a scientific approach behind it, involving interchangeability. The modern dimensional metrology for manufacturing industries was initiated with the evolution of concept of interchangeability. In small scale production, it was very much possible to check each part individually and make adjustments if required, but this hand-fit technique was not enough to meet the requirements of mass production. With the latest advancements in production techniques, the identical components are being manufactured in large quantities on the basis of interchangeability. That means, if the components are being manufactured on large scale, then any component should fit satisfactorily into any of the mating counterpart. This requires highly skilled manpower and special purpose machines. The manufactured parts can only be interchangeable, if their relevant dimensional features are being inspected properly at various stages during manufacturing. The products are precisely examined either during production or after, in order to maintain product standardization and conforming universally recognized dimensional standards. According to recent studies, predictions of measurement accuracy are supposed to be the most important aspect in mechanical parts inspections. Dimensional metrology has diversified objectives in tool room, machine shop, press shop, plastic shop, die casting shop and assembly shop of a modern manufacturing plant [4]. Production of quality components majorly depends upon designing and tolerancing of products, selection of production processes and applying suitable measurement methods. Precision dimensional metrology plays a significant role in providing assurance that the manufactured product, which has been specified in terms of nominal size and allowable variations, meets the design specification. By using state-of-art dimensional metrology techniques, tighter tolerances can be provided to the components resulting into longer in-service life, quieter operations and increased efficiency. In manufacturing, dimensional metrology is the most prevailing branch of precision metrology. It covers different techniques and instruments to be used for making physical measurements to assess the conformance of components to design specifications. During manufacturing, all the components cannot meet exact size condition as per the design specifications, due to inherent sources of error. Dimensional control of a manufactured component is not only to check it for exact size, but to control and limit the size variations with in prescribed limits. Every part feature has a prescribed tolerance, and inspecting a part delineates the degree of disagreement between the actual part and its blueprint [5].

2.3. Advancements in Dimensional Metrology

Currently, the growing manufacturing industry with miniaturized components, complex geometry products, tighter tolerances and rigorous quality control is facing new challenges. To meet these challenges, there is a need of robust and precise dimensional metrology infrastructure, emphasizing the importance of modern dimensional metrology applications in manufacturing. With continuous development of manufacturing industry and increasing demand for an economical way of production, the metrological characterization of components based upon geometrical dimensioning and tolerances has become extremely important. High precision dimensional metrology has become an indispensable part of modern industrial applications, quality control and related research areas [6]. In recent years, precision metrology has come up with many steps ahead in accordance with the introduction of advanced manufacturing techniques and requirements about the functionality of complex parts. Recent developments in dimensional metrology are capable enough to provide reproducible holistic and valid measurement information for optimization of processes. Thus, in addition to the possible automation of manufacturing processes, compliance of products with standard and functional requirements can be evaluated and adjusted accordingly.

The metre convention given in 1875 was replaced by a new definition for realization of SI unit "metre" with the help of speed of light in vacuum. This metre definition is disseminated to shop floor of manufacturing industries with the help of He–Ne laser and laser interferometers. These laser interferometers in turn are used for calibration of gauge blocks, line scales, length bars and other precision instruments [7]. With technical advancements in dimensional metrology, the initial two-point dimensional measurements were replaced by profile projectors, microscopes, digital readouts, LVDT probes and coordinate measuring machines. Different optical measurement techniques are also being used for vital dimensional measurements. The applications where two-point measurements are not useful, such as profile of automobiles and aircraft components, fringe projection method based on triangulation is used. For surface characterization of various electronic and optical components, white light interferometry is used. Coordinate metrology has emerged as a boon for manufacturing metrology, judging the deviation by carrying out dimensional measurements on various points of workpiece surface and replacing the simple devices like calipers and micrometres. Coordinate measuring machines (CMMs) can make dimensional measurements for a large range of artefacts. CMMs combined with laser trackers can measure large objects such as aircrafts, while micro-CMMs can make measurements in nanometre range [8]. In near future, the conventional CMMs will not be able to meet accuracy demands of manufacturing industries; thus, to overcome this problem, modification in CMMs structure and software will be required. For dimensional characterization of geometrically complexed components, multidisciplinary measurement techniques such as coordinate laser scanning, multiangle scanning, pneumatic methods and ultrasonic gauges are used. Multisensor CMMs are being used for dimensional, mechanical, optical and electrical characterization of different components.

For faster detection of dimensionally bad parts, advance holistic measurement techniques such as moiré fringes, holography and photogrammetry are also being used. X-ray computed tomography and terahertz tomography are being used to analyse the volume of workpiece by a single measurement. Some of the scanning probe microscopes are used as imaging tool for dimensional measurement of nanofeatures on a component. In order to maintain accuracy at nanolevel and qualify them for dimensional metrology, the calibration of these SPMs is done using laser interferometers and standards for tip characterization. Metrological atomic force microscopes (MAFMs) with built-in laser interferometers disseminate traceability for nanometrology through calibration of various step height standards and standard gratings, which are used as calibration standards for SPMs and AFMs. Precision dimensional metrology as a combination of various measurement techniques in one measurement device with increased resolution and accuracy offers amazing possibilities and becomes crucial in micromanufacturing and nanomanufacturing by using novel principles of measurement data fusion [9]. It can be observed that dimensional measurement of component features is one of the primal activities in manufacturing industries. As the components are repeatedly checked for their specified dimensions, using measuring instruments during manufacturing, it becomes crucial to calibrate the measuring instruments periodically to ensure quality. In order to identify manufacturing deviations, the measurement accuracy must be ten times better than the manufacturing accuracy. Calibration is defined as the process of comparing a device with an accurate measurement standard to eliminate variations, and the frequency of calibration depends upon the utilization of instrument.

2.4. Dimensional Measurements: Influencing Cost-Effectiveness

The manufacturing metrology is treated as the major cost factor during production. While the fact is that, if dimensional measurement accuracy is not kept in consideration during manufacturing, one might make wrong decisions resulting into coarser sampling and higher measurement uncertainties, hence making it a costly affair. Thus, a balance should be maintained amongst functional requirements, dimensional measurement methods, accuracy, significance of measurement results, traceability and measurement uncertainty [9, 10]. There is a push for less operator involvement in modern manufacturing plants and it is expected that metrology shall shift towards in-process adjustments for real time optimization of process parameters using intelligent sensors. In order to cut down overall wastage in a manufacturing industry, there is a requirement of dimensional metrology as a "toolbox" to aid manufacturing. The toolbox shall be comprised of various instrument modules for dimensional measurement of different features on the workpiece [11]. Hence, it can be stated that precise dimensional measurement in manufacturing provides proper structure, reduces waste, promotes fair trade and leads towards economical production. The major factors affecting dimensional measurements are as below:

- The equipment selected for measurement, its working condition, maintenance and calibration. It sternly influences the measurement uncertainty and reliability of measurement results. Equipment is the most critical contributor during uncertainty evaluation.
- The environment during dimensional measurement influences measurement results and uncertainty. Different variables such as temperature, relative humidity, air pressure, luminous intensity and vibrations affect the measurement performance. It is very important to identify appropriate environmental factor and optimize that for dependable measurements.
- Standard calibration and testing procedures should be followed by the operator. It is very important to have consistent measurement techniques.
- The operator should be confident and adequately trained to facilitate the measurement process and perform quality work in order to avoid any negative impact on measurement results.

There are some guiding principles for reliable dimensional measurements, described below [12]:

- Right measurement: Measurement made to satisfy specified requirements.
- Appropriate equipment: Measurements should be made using equipment and procedures fit for purpose.
- Well-educated/trained people: Measurement people should be well informed, well trained, competent and properly qualified.
- Correct and validated procedures: Measurement procedures in line with national and international standards should be there for all measurement activities.
- Continuous reviews: There should be regular assessments of the technical performances of measurement facilities and standard procedures.
- Convincing consistency: There should be demonstrable repeatability and reproducibility of measurement results.

Superior dimensional measurements can be made by considering under mentioned components [1]:

- Understanding various metrological concepts such as accuracy, precision, repeatability, reproducibility, measurement uncertainty, traceability, calibration, acceptance criteria and tolerances.
- Validating measurement methods and using only validated methods.
- Using international standards of units to avoid discrepancies.
- Identifying error sources and evaluating overall measurement uncertainty.
- Using geometrical tolerances.

2.5. Coherence Between Laboratory Metrology and Industrial Measurements

Direct dimensional measurements can still be managed with the advance industry needs, but there is a huge gap existing between state-of-art facilities and industrial requirements. With continuous tightening of dimensional tolerances in manufacturing industries, the requirements of precise dimensional measurement and inspection instruments become essential for the manufacturer, where precision metrology embraces the inspection methods, production metrology, measurement algorithms, tolerance representation and integration of metrology into organization's quality system [11]. Better dimensional measurement practices lead to a temporary drop in the productivity initially, but in long terms improved measurement capabilities open avenues to significant productivity gains. Advance dimensional measurement techniques are creeping into manufacturing sectors and are dislodging the conventional measurement processes to cater tighter tolerances in design and production. In some cases, practically oriented measurement standards are being embedded into design and implementation in the industry [13].

3. Egression of Nanometrology from Precision Dimensional Metrology

The industrial needs in terms of precision manufacturing are continuously growing with scientific developments; thus, nanometrology has become an integral part of modern production processes. In recent years, it has been observed that the enhancement in quality of products has a correlation with advancements in accurate and precise dimensional measurement processes and techniques. The advancement in metrology is continuously growing due to evolution of nanotechnology. In industrial metrology, realization of manufacturing accuracies in nanometric range is need of the hour to survive worldwide competition. As the dimensional tolerances of products become tighter, the product quality based upon geometrical product specification enhances and to fulfil this demand, advanced computer-aided production metrology is to be explored extensively to control manufacturing. With industrial developments, interchangeability of parts required a fresh management, due to which sophisticated and cost-effective production metrology and inspection techniques were created for quality control. In the area of production metrology, geometrical measurements are most significant for modern quality management and enhanced productivity [14, 15]. Nanolevel dimensional measurements for advanced semiconductor and core mechanical engineering industries can be carried out with the help of advance laboratory research in National Metrology Institutes, so that the product conforms to the design specifications. Though, with riotous development in precision manufacturing machines and advance production techniques such as lithography, molecular self-assembly, electrically-induced nanopatterning, laser ablation and focused ion beam lithography, it has become possible to manufacture nanosize dimensional features and functional elements, yet it has been observed that there is a disruption between the laboratory research and industrial applications in the field of nanometrology [16]. In addition, the absence of international measurement standards in nanometrology consisting of calibration of nanometrology instruments, nanolevel geometrical tolerances, new measurement parameters in nanometrology and standard procedures for reproducible nanolevel measurements is a prominent obstacle in catering current industrial demands and setting up an acceptance criteria for industrial nanometrology. In mechanical engineering, the intention of using industrial nanometrology can be supported by following attributes:

- Reliability of measurements
- Comparability of measurements, while done with different measurement systems.
- Repeatability and reproducibility of measurements
- Usage of economically reasonable measurement equipment
- Capability of performing fast measurements
- Involvement of lesser sources of error
- Automated measurement processes
- Self-calibration capability

The functioning of any nanocomponent largely depends upon the optimization of dimensional tolerances and selection of appropriate machining and measurement processes. So far, there are no tolerancing systems and guidelines for microsize and nanosize mechanical components to attain desired performance [17]. For effective implementation of nanometrology in manufacturing, to produce cost-effective quality products with highly stable production processes, it is extremely important to have coordination between product manufacturers, National Metrology Institutes, equipment manufacturers and national/international standard organizations [18]. For successful integration of nanometrology with manufacturing, it becomes essential to define new tolerancing system and measurement strategies for nanorange, identify new measurand, revising existing parameters according to their utility in nanometrology and restructuring of international standards for nanometrology.

4. Role of NMI (NPL India)

National Metrology Institutes (NMIs) establish national measurement systems, in order to maintain and disseminate measurement standards for base units and metrological capability by providing traceable calibration and testing services along with significant research outcomes to nation's economic growth and ascertains that measurements done are fit for purpose.

4.1. Responsibilities of CSIR-NPLI

CSIR-National Physical Laboratory India (NPLI) maintains national measurement infrastructure and works for scientific metrology in the form of establishment of unit of measurements, realization of SI units by maintaining primary national standards, maintaining unbroken chain of traceability (Fig. 1) and developing new measurement methods with high degree of accuracy [19].

Traceability is defined as the characteristics of measurement observations wherein these observations are correlated to stated references (national or international standards) through documented unbroken chain of comparisons, all having stated uncertainties and contributing towards measurement uncertainty [20]. At CSIR-NPLI, the traceability chain for various dimensional measurements is established as shown in Fig. 2.

CSIR-NPLI was established to take the responsibility of physical measurements based on SI units under the subordinate legislation of Weights and Measures Act 1956. NPLI in coordination with supporting organizations such as Bureau of Indian Standards (BIS), Legal Metrology and National Accreditation Board for Testing and Calibration Laboratories (NABL) ensures that the measurement system across country is accurate and legal, resulting into fair global trade and customer satisfaction.

4.2. Customers Catered

At NPLI, we support various industries (Tata Motors, Ashok Leyland, Maruti Suzuki, Eicher tractors, Philips India, UltraTech Cement, Ambuja Cement, Binanai Cement, J. K. White Cement, TATA Steel, Shri Ram Industries, Diesel locomotive works, Esser Oil Ltd., Blue Star, Crompton Greaves, Godrej and Boyce Mfg. Co. Ltd., Kirloskar, L & T, Rapid Metro Rail Gurgaon, Jindal Steels and various NABL accredited testing & calibration laboratories, etc.), government organizations (BARC, ISRO, IOCL, IDEMI, NTPC, Naval Dockyards, RRSL, SAIL, MoD, NIE, MDNL, BEL, HAL, BHEL, NCCBM, MSME, ERTL, CPCB, BSF, DEAL, CPWD, CMTI, ETDC, Weights & Measures, Air Force, Air India, Central Railways, NTH, Ordnance Factories, various CSIR laboratories, and R& D centre for Bicycle, etc., Research & Development institutes (IITs, DRDO, AIIMS, etc.) and SAARC NMIs (NBSM Nepal, BSTI Bangladesh, MUSSD Sri Lanka, BSB Bhutan, MSMU Maldives and ANSA Afghanistan) by providing precision measurement services, traceable calibration and testing services, consultancies and developing devices.

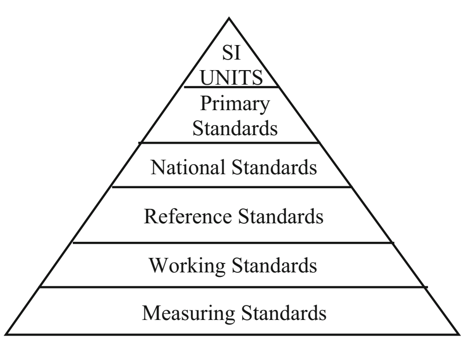

Fig. 1 Measurement traceability pyramid

5. Conclusion

Present investigation describes the appositeness of precise dimensional measurements in industrial applications. It emphasizes on imparting sufficient attention towards the requirements and implications of error-free dimensional measurements during whole manufacturing process and analysing the consequences in terms of desired functioning of the manufactured component. The current article provides an overall view of fast-growing manufacturing industry and the challenges faced in quality control. To overcome these challenges, applications of advance dimensional metrological techniques appear to be most suitable way. Key capabilities to manufacture quality products are precise modelling, geometrical dimensioning and tolerancing, selection of production processes, process control and selection of measurement methods. Tighter tolerance are provided for better quality control, longer life, faster and quieter operation, enhanced efficiency, maintained interchangeability with preserved functioning and cost-effectiveness. Precise dimensional metrology plays an important role in assuring that the manufactured product meets design specifications and performs as desired. In future generation, the advanced and economical manufacturing will largely depend upon extremely precise and accurate dimensional measurements to be carried out with the help of robust, cheap and fast instruments. Considering the shift from macro-manufacturing to nanomanufacturing, it is important to understand that the crucial measurement parameters also change; thus, the designing and production processes should be adopted accordingly. Dimensional metrology is a crucial factor for industrial sustainability; thus, adequate attention is to be paid to precise measurement needs, and precision dimensional metrology is to be kept at highest priority among the essential requirements for manufacturing of quality products.

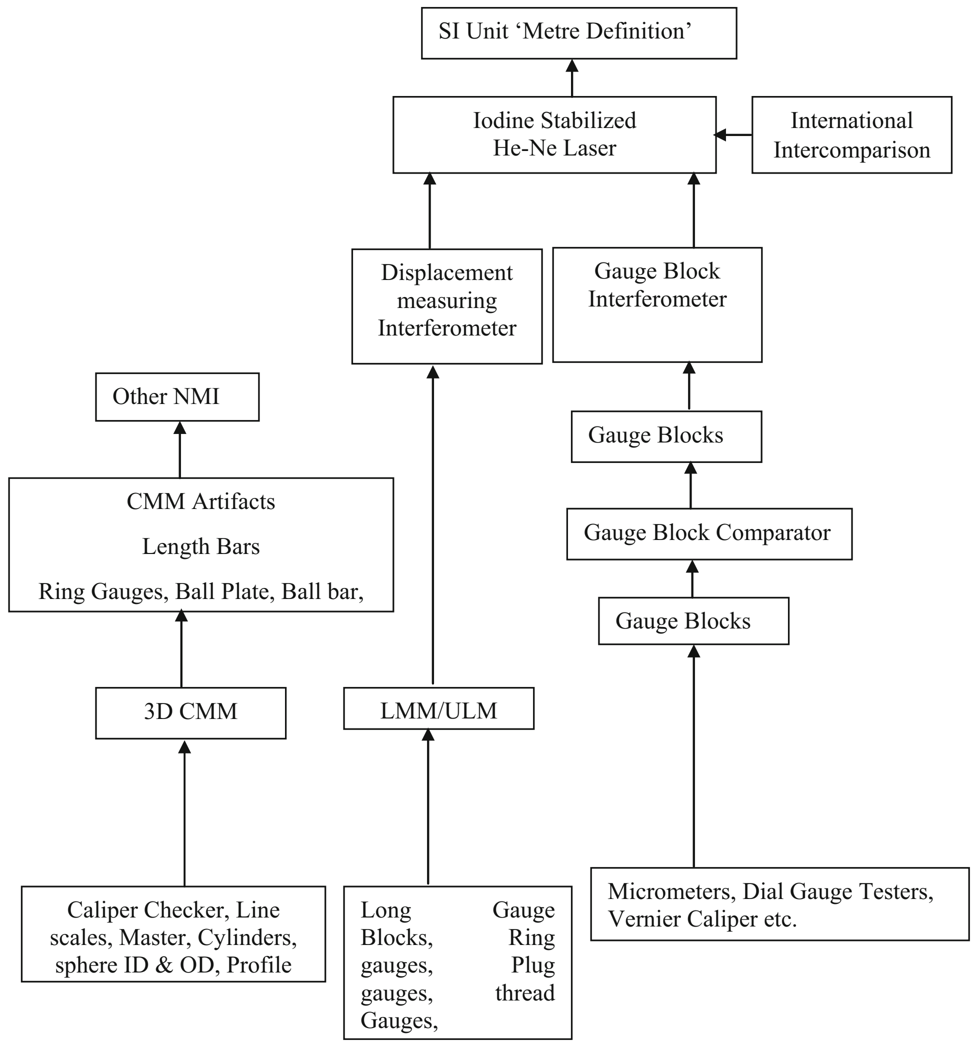

Fig. 2 Traceability chain for dimensional metrology at CSIR-NPLI

Acknowledgements Authors are thankful to Director, National physical laboratory for his constant support and continuous motivation to write this article.

References

[1] Y. Qin, A. Brockett, Y. Ma, A. Razali, J. Zhao, C. Harrison, W. Pan, X. Dai and D. Loziak, Micro-manufacturing: research, technology outcomes and development issues, Int. J. Adv. Manuf. Technol., **47** (2010), 821–837

[2] G.N. Peggs, Transactions on Engineering Sciences, WIT Press, 2001, ISSN 1743-3533, UK

[3] H.N. Hansen, K. Carneiro, H. Haitjema and L. De Chiffre, Dimensional micro and nano metrology, Ann. CIRP, **55** (2006), 721–743

[4] G. Wilkening and H. Bosse, Nano- and micrometrology – State-of-the-art and future challenges, MAPAN-J. Metrol. Soc India, **20** (2005), 125–151

[5] E.B. Brousseau, S.S. Dimov, D.T. Pham, Some recent advances in multi-material micro- and nano-manufacturing, Int. J. Adv. Manuf. Technol., **47** (2010), 161–180

[6] V Srinivasan, Standardizing the specification, verification, and exchange of product geometry: Research, status and trends, Comput. Aided Des., **40** (2008), 738–749.

[7] M. Bahrawi, N. Fareed, Application of a commercially available displacement measuring interferometer to line scale measurement and uncertainty of measurement, MAPAN-J. Metrol. Soc India, **25** (2010), 261–266

[8] K.J. Stout, M.N. Durakbasa and P.H. Osanna, Quality assurance - Have we specified it the wrong way around?, WEAR, **5/6** (2009), 511–514

[9] A. Weckenmann, P. Kraemer, J. Hoffmann, Manufacturing metrology –State of art and prospects, Proc. ISMQC, Madras INDIA (2007), 1–8.

[10] H. Kunzman, T. Pfeifer, R. Schmitt, H. Schwenke and A. Weckenmann, Productive metrology – adding value to manufacture, CIRP Ann. Manuf. Technol., **54** (2005), 155–168.

[11] https://www.unido.org/role-measurement-and-calibration-manufacture-products-global-market-guide-small-and-medium-sized-enterprises (Accessed in May 2018)

[12] I. Cristofolini, S. Filippi and C. Bandera, The role of product feature relations in a knowledge based methodology to manage design modifications for product measurability, Int. J. Prod. Res., **47** (2009), 2373–2389

[13] Y. Zhao, X. Xu, T. Kramer, F. Proctor and J. Horst, Dimensional metrology interoperability and standardization in manufacturing systems, Comput. Stand. Interfaces, **33** (2011), 541–555.

[14] Y. Hong and T. Chang, A comprehensive review of tolerancing research. Int. J. Prod. Res., **40** (2002), 2425–2459.

[15] A.K. Srivastava, Role of NPL-India in nanotechnology and nanometrology, MAPAN-J. Metrol. Soc India, **28** (2013), 263–272

[16] T. J. B. M. Janssen and D. Roy, Nano-science and nano-metrology for societal benefits, MAPAN-J. Metrol. Soc India, **28** (2013), 237–238

[17] R. J. Lazos-Martı´nez and N. Gonza´lez-Rojano, Nanometrology in emerging economies: the case of Mexico, MAPAN-J. Metrol. Soc India, **28** (2013), 299–309

[18] X. Jiang and D. J. Whitehouse, Precision metrology, Phil. Trans. R. Soc. A, **370** (2012), 4154–4160

[19] http://www.nplindia.in/ (Accessed in June 2018)

[20] https://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf (Accessed in June 2018)