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New developments in coordinate measuring machines for manufacturing industries

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Abstract. There have been substantial improvements in measurement systems in order to meet fluctuating market demands. This rapid change and development in measurement technology has primarily been governed by demands of accuracy and precision from aerospace, automotive and other manufacturing industries. Coordinate measuring machines (CMMs) available with different technologies and configurations has efficiently been fulfilling customer demands for more than a decade. Though, current CMMs can meet needs of rapid and increased demands of customers to a greater extent but still there is lot of scope for improvement and development in CMMs. The globalization of manufacturing has resulted in development of variety of complex products and miniaturization of mechanical components. The technology of micro/nano-scale 3D measurement is still a bottleneck for industries. Therefore, precise and accurate system which is flexible enough to deal with complexities of parts and micro & nano range products has to be investigated. In this paper, comprehensive review concerning CMMs with capabilities to measure micro/nano features has been presented. This work has also discussed different methods to estimate measurement uncertainty, as well as performance evaluation of CMMs. Moreover, novel concepts such as intelligent CMM, multi-sensor CMM, virtual CMM have been presented.

Keywords: Coordinate measuring machine (CMM); uncertainty; intelligent CMM; micro/nano CMM; virtual CMM; multi-sensor CMM

1 Introduction

Coordinate measuring machines (CMMs) are most common devices being used for 3D inspection of physical components in manufacturing industries. CMMs are mechanical systems which involve movement of measuring probe to determine coordinates of points on work piece surface. They are primarily composed of four components: main structure, probing system, control or computing system, and measuring software. Application of CMMs encompasses wide measurement range from ship or aircraft industries to miniaturized semi-conductor industries. CMMs have drastically revolutionized quality process in aerospace, automotive, medical, mold and die, ship building industries, etc. They not only provide high accuracy and precision but better convenience, simplicity and high speed of their operation to measure range of products. They can exhibit many possibilities such as measurement automation, graphic visualization of results, ability to integrate with computer-aided design/computer-aided manufacturing systems in order to make measurement process efficient and reliable [1]. Industrial applications of CMMs generally include process control, quality assurance of manufactured components, fixture verification, machine alignment, etc. Over the past several decades, CMMs have successfully superseded conventional methods of measurement such as gauges, hand tools, etc., resulting in reduced time and effort of quality control operations. Since their invention in late 1950s and gradual introduction into manufacturing through early '60s, CMMs have undergone tremendous advancements. With advent of technologies such as intelligent CMMs, virtual CMM, multi-sensor system, etc., industrial metrology have taken a huge leap as long as precise and efficient operation of CMM is concerned. Increasing demands of 3D measurement for smaller products have necessitated the need to develop micro/nano-CMMs with very high resolution. A lot of research effort for CMMs which can measure products in micro/nano range can be found in literature. Moreover, ever increasing demands of higher performance, better reliability, and improved productivity in manufacturing industries require measurement of tighter geometric tolerances. Therefore, with strict requirement of geometric tolerances it has become mandatory to determine uncertainty associated with measurement methods. In fact, large numbers of methodologies, procedures and techniques have been proposed in literature to estimate task specific measurement uncertainty.

In this paper, comprehensive review regarding uncertainties associated with CMM measurement and evolution of micro/nano CMMs has been carried out. This work has also addressed concepts of intelligent CMM, virtual CMM,

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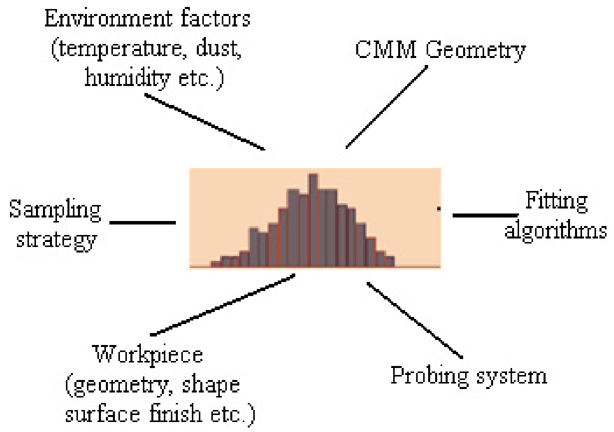

Fig. 1. Sources of uncertainties in CMM [2].

as well as multi-sensor technologies. This paper has been divided in three main sections: measurement uncertainties associated with CMM, evolution of micro/nano CMMs, and CMM advancements.

2 Measurement uncertainties associated with CMM

Widespread application of CMMs in industrial dimensional metrology can be attributed to their ability to measure variety of characteristics on a range of products. However, CMM measurements are accompanied with unlimited sources of variability such as workpiece position and orientation, sensor type and configuration, environment conditions, sampling strategy, computational strategy, etc. [2]. Actually, measurement with CMM is a multi-step process where each stage as shown in Figure 1 contributes to overall measurement uncertainty. It is worth noting that though there are many sources of variation in CMM but in fact only few of them predominates. For instance, thermal effects are commonly significant but with increase in measuring speed, dynamic geometric effects also come into existence.

Measurement uncertainty can be defined as uncertainty of results of a measurement on CMM as per Guide to the expression of uncertainty in measurement [3]. According to Taylor and Kuyatt [4] measurement outcome should include a quantitative statement of its uncertainty for completeness and valid judgment of final results. When measurement uncertainty is associated with measurement of particular feature using specific measurement plan, it is known as task specific uncertainty [5]. Task specific uncertainty depends on number of factors such as sampling strategies, measuring object, probing technique, environmental conditions, evaluation software, measuring equipment, etc. [6]. Factors that affect measurement uncertainty of specific task can be categorized into following two categories [7]:

- **Extrinsic factors**: CMM operator, workpiece fixturing variation, workpiece form error, sampling strategy, thermal properties, dirt or coolant, etc.
- **Intrinsic factors**: Multiple styli (fixed star probe or articulated stylus), scanning probes, rotary tables, CMM dynamic effects, etc.

The different factors that generally influence measurement results of CMMs have been depicted through cause and effect diagram shown in Figure 2.

Evaluation of measurement uncertainty is a complicated procedure which involves variety of sources of errors [8]. Although, it is not an easy exercise to determine overall measurement uncertainty but still it has been attracting lot of research interest. The increased interest in determining measurement uncertainty can be attributed to following reasons [7]:

- It establishes whether a particular CMM meet accuracy requirements for a given measurement task or not.
- It identifies the effect of any change in temperature, probe configuration, sampling strategy, etc., on measurement results.
- It measures quality as well as applicability of measurement results.

As a result of increased demands for better accuracy and precision, efforts to determine potential sources of measurement uncertainties have also been increasing. For instance, work of Weckenmann et al. [6], where contributions of different uncertainties have been identified on CMM measurement results through measurement of car body. A comprehensive review of techniques in which Wilhelm et al. [5] estimated task specific uncertainty for CMMs represent significant contribution in this area. Butler [9] identified measuring probe as one of the most important sources of error in CMM measurement results. According to author, measuring probe constitutes about 60% of errors in measurements performed on CMM. It is very important for CMM user to verify probing accuracy once it has been used over a period of time. A fuzzy knowledge based models to determine 3D probing accuracy for one- and two-stage touch trigger probes has been proposed by Achiche and Wozniak [10]. The generated algorithm was based on genetic algorithm and used hybrid coding, binary for rule base and real for database. Application of CMM for measurement purposes has many limitations that need to be considered for accurate measurements. For example, evaluation of form error for ultra-precision freeform surfaces is a challenging exercise because it requires highly precise measuring methods. Least square based surface matching method has most commonly been utilized to align measuring freeform surface on design surface for assessment of form error. Inaccurate surface matching method results in misalignment of coordinate systems of two matching objects which cause serious measurement error. Therefore, investigation has been carried by Ren et al. [11] to estimate uncertainty associated in application of least-squares-based form characterization method. Over the last few decades, efforts to identify different sources of errors and their compensation methods have increased extensively. Zhang et al. [12] proposed techniques to compensate for geometric positioning errors and thermal effects in case of bridge type 3D

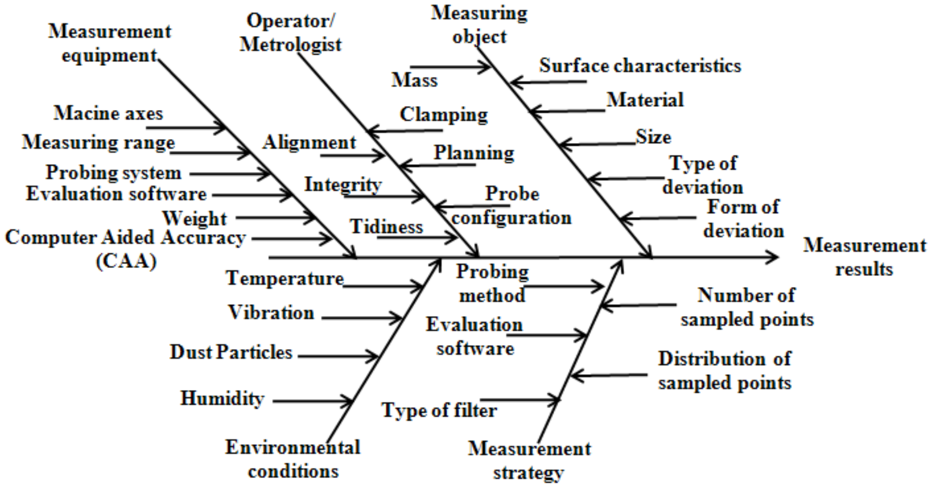

Fig. 2. Factors responsible for uncertainties associated with CMM measurements [6].

CMM. In fact, an online error compensation system based on three laser optical multi-degree-of-freedom measurement systems (MDFM systems) for CMMs has been presented by Huang and Ni [13]. This system provided flexibility to measure error components by using both on-line and off-line measurement methods. In this work, mathematical models to synthesize error components and to predict errors at probe stylus tip have also been developed. Hermann [14] proposed a volumetric error correction model including both gravitational and spring force effects to determine error components of carriage and pinole in CMMs. Moreover, Che and Ni [15] introduced methodology for on-line assessment of measurement uncertainty on CMM. In this paper, uncertainty propagation of structured-light optical CMM has been analyzed to compute uncertainty of a single point in world frame and uncertainty of distance measurement. In fact, first-order Taylor expansion has been utilized to compute uncertainties while Monte Carlo simulation has been employed to validate uncertainty models. Since, temperature affect CMM measurement results significantly therefore thermal errors have to be taken into account for better measurement results. To determine influence of temperature on measurement, Kruth et al. [16] presented an approach which computed thermal deformation of individual machine components using temperature distributions of CMM. Teeuwsen et al. [17] also presented an approach including non-rigid body effects as well as thermal effects in order to compensate for systematic errors of CMMs. In this work, polynomial fitting procedure has been used to describe individual error components for CMMs. Kim and Chung [18] proposed a volumetric error model to compute thermal and geometric errors for CMMs. In this effort, thermal errors have been modeled using exponential functions while geometric errors have been determined using off-line calibration procedure. Authors have also applied infinitesimal matrix transformation in this work to correct position error due to geometric imperfections and utilized thermal drift of spindle for determining thermal errors. Analytical evaluation of uncertainty of coordinate measurements by Jakubiec [19] has taken into account important factors such as influence of kinematic errors of CMM, probing head errors and temperature influences. This work has resulted in models which can successfully evaluate uncertainty of measurement of geometrical deviations such as straightness, coaxiality and perpendicularity, etc. Moreover, Samuel and Shunmugam [20] identified and verified techniques to evaluate error in circularity and sphericity measurement using CMM.

Although, processing software contributes significantly to overall measurement uncertainty but it has often been ignored in literature. However, Shakarji and Raffaldi [21] identified processing software as one of the important sources of error in metrology using CMM. In this work, authors successfully described different kinds of fitting software, associated problems and their various causes through different examples. Practical and easy to implement steps that can be undertaken to reduce these problems have also been suggested. Most often, errors due to software arises either as a result of wrong implementation or incorrect software development process. Software error from implementation stage occurs as a result of sampling strategy, filtering methods, outlier handling, interpolation/extrapolation, etc. Poor software architectural design, inadequate testing, lack of knowledge, etc., represent some of potential error sources introduced during development stage. Phillips et al. [7] have also described several methods to identify loopholes in CMM simulation software. In this paper, authors identified different factors such as uncertainty of measurand, simulation fidelity, simplified, incomplete or incorrect mathematical modeling, input parameters, coding errors, methods of testing, etc., that should be considered while testing of CMM simulation software. Indeed, explanation and applicability of available techniques such as sensitivity analysis, expert judgment, substitution, computer simulation, measurement history, etc., for CMM uncertainty evaluation can be studied in ISO technical report [22].

CMMs have been dominating measuring instruments in dimensional metrology for the past several decades. Therefore, to achieve desired speed, accuracy, and flexibility, it is very important to evaluate performance of CMM on day to day basis. A comprehensive review of different methods and techniques for monitoring CMM performance can be found in research work carried out by Cauchick-Miguel et al. [23]. In this analysis, testing methods have been identified and classified based on mechanical artefacts, optical techniques and opto-mechanical devices. This work has also outlined various artefacts for successfully evaluating probe performance. Meanwhile, Singhose et al. [24] investigated performance of CMMs in presence of structural vibrations and successfully improved CMM repeatability over a range of operating parameters. Artefact by Hansen and De Chiffre [25] can be utilized for performance verification of both optical and mechanical CMMs. The 2D artefact has been developed for both optical and mechanical probing and calibration. Arriba et al. [26] also identified various artefacts for calibration, error correction and performance evaluation of large CMMs. They suggested light weight ball plate as the most economical artefact that can be used up to 5 m CMM axis length. 3D-calibrated multi-ball beams have identified to be least economical artefacts that can be utilized for any CMM size. Furthermore, integrated model by Abbe et al. [27] can be used to determine reliability of geometric calibration for CMMs. This approach provided information regarding uncertainty of calibration as well as explains how error propagates on linear system thus representing parametric errors of CMM. Curran and Phelan [28] described a method in which telescoping ball-bar has been used to evaluate CMM performance. This method can be very useful to quantify CMM machine errors such as squareness and positional errors. Moreover, Sansoni et al. [29] evaluated measurement performance of optical 3D sensor based on projection of structured light. A substitution method has been presented where repeated measurements are carried out on calibrated object using CMM. The optomechanical hole plate has identified to be suitable artefact for performance evaluation of both mechanical and optical CMM measurements [30]. It has also been recommended by De Chiffre et al. [30] that optomechanical hole plate is a suitable reference artefact for traceability of CMMs particularly optical CMMs which seems to lack available artefacts. CMM has successfully been monitored with cost-effective and less time consuming substitution method by Weckenmann and Lorz [31]. In this work, methodology for monitoring horizontal-arm CMMs with calibrated sheet metal series parts has been proposed. According to authors, use of standardized artefacts such as ball plates, hole plates, ball bars or step gages is expensive since it require special expensive fixtures, CNC routines, evaluation programs and training courses for operators. However, proposed substitution method in which measured work pieces were used as calibration artefact and CMM as comparator provided economical procedure to monitor CMMs. Woźniak [32] evaluated repeatability of modular probes of CMMs in order to test positioning error. Testing of proposed method on Renishaw TP20, Zeiss VAST Gold and VAST XXT probes identified that magnetic joint positioning error ranges between 0.7 μm and 2.8 μm. Zhang et al. [33] proposed a methodology to compute volumetric errors of CMM. In this paper, models to calculate error components for pitch and yaw movement, squareness and straightness errors, roll errors at any particular point have been introduced. Experimental investigation showed that application of presented methodology would simplify machine calibration and improve machine accuracy. Moreover, Savio et al. [34] identified two methods for measurement traceability of freeform geometries on CMMs. In this paper, application of proposed methods i.e., use of modular freeform gauges and uncalibrated objects has been shown through calibration of turbine blade. Lim and Burdekin [35] also proposed a system which employed 540 mm long I-beam hole bar for calibration of multiaxis CMMs. In this procedure, firstly parametric error components were identified by probing artefact at different orientations within working volume. Then, these error components were transformed to CMM volumetric error using formulae obtained for rigid-body motion of CMM. Kinematic model of CMMs developed and evaluated by Barakat et al. [36] can also be utilized to compensate for geometric errors as well as improve volumetric performance of CMMs. Similarly, Schwenke et al. [37] presented a method to outline geometric errors of CMMs using single tracking interferometer. This approach provided several benefits such as no requirement of device alignment, unlimited maximum size of working volume, simple data structure, etc. This method can successfully be employed on large horizontal arm machines as well as small precise machines. Keeping in mind the increased demands of better CMM performance, different designs of artefact have been evaluated and assessed for measurement repeatability and accuracy by Agapiou and Du [38]. Silva et al. [39] proposed a novel approach to evaluate volumetric performance of four axis CMMs. In this method, ball plate consisting of seven highly accurate spheres has been used for uncertainty analysis and error assessment of CMMs. The evaluation of procedures and different artefacts for testing CMMs with optical distance sensors can be found in investigation carried out by Carmignato [40]. Experimental procedure employing fringe counting interferometer as reference standard has been used by Muelaner et al. [41] to estimate measurement uncertainty for CMMs. This method involved comparison of measured coordinates with calibrated reference points. Recently, Acko et al. [42] have developed methods to guarantee traceability of 3D measurements for gears. Three different artefacts viz. tetrahedron artefacts, freeform verification artefacts and large gear artefact have been established for calibration of different types of CMMs.

3 Evolution of micro/nano CMMs

Miniaturization and modularization in micro-system technology have resulted in need of 3D CMMs which can provide measurement uncertainties in the range of 0.1 μm [43]. According to [44], Nano CMM is a 3D

CMM with a volumetric uncertainty of 25 nm ($k = 2$) in a measuring volume $50 \times 50 \times 4$ mm. Actually, micro/nano CMMs have received lot of attention in the past few decades due to their widespread applications in precision measurement of micro gears and balls, hardness indenters, semiconductor industries, material science, precision engineering industries.

Efforts of Takamasu et al. [45] who introduced basic concept of nano CMM and Jager [46] who described nanopositioning machine with integrated nanoprobes illustrates importance of this area in research fraternity. In fact, these CMMs require very high accuracy and precision therefore transformation from traditional CMM design principle to micro/nano CMMs is not an easy task. A lot of research to develop ultra precise CMM has been carried out to achieve efficient measurement of microsystems. For instance, development of CMM with $50 \times 50 \times 50$ mm measuring volume and sub-micrometer volumetric uncertainty at National Physical Laboratory (NPL) by Peggs et al. [43], Silicon-based Nanoprobe System by Haitjema et al. [47], sub-atomic measuring machine (SAMM) by Hocken et al. [48], design principles of micro-CMM with expected measuring range $25 \times 25 \times 10$ mm and resolution of 1 nm by Fan et al. [49] represent some of the successful developments in this field. Scientists at Germany's national metrology institute [51] successfully transformed microscope into micro/nano CMM. It provided nanometer resolution in measuring volume of 25 mm $\times$ 25 mm $\times$ 5 mm. This CMM incorporated commercial nanopositioning system with integrated laser displacement sensors. Fujiwara et al. [50] evaluated thermal drift and tilt angles which are critical properties for the development of nano-CMM. Moreover, in this work authors presented a prototype of Nano-CMM made of low thermal expansion iron steel and suggested a construction to reduce effects of tilt angles. Fan et al. [52] enhanced structural accuracy and performance of micro-CMM by incorporating design concepts such as arch-shape bridge for better stiffness and thermal accuracy. They also suggested co-planar stage for less Abbe error, linear diffraction grating interferometer for position sensing to nanometer resolution and focusing probe to guarantee nanometer stability. With conventional CMMs, object can be measured with measurement uncertainties only up to 1 mm. Therefore, efforts to develop CMMs which can perform measurements of challenging objects such as small setting ring standards, small diameter wires, etc., have been in great demand. Hermann [53] presented overview of different designs and construction of small CMMs with resolution up to 0.01 μm and 0.1 μm measurement uncertainty. These machines provided several features such as coarse and fine positioning using piezo-motor based control system, application of different probes, error correction techniques, interpolation algorithms, etc. Ruijl [54] also introduced highly precise CMM with measuring uncertainty of 50 nm in a $100 \times 100 \times 40$ mm measuring volume. Brand et al. [55] developed CMM for measuring microsystem components with uncertainty less than 0.1 μm and measuring range of 25 mm $\times$ 40 mm $\times$ 25 mm. It was a special kind of CMM with optical measurement system and two tactile 3D-micro-sensing systems. One of the sensors made use of very small probing balls with diameters 25 μm and probing forces as low as 1 μN while other sensor was based on silicon boss-membrane with piezo resistive transducers. Moreover, opto-tactile 3D-sensor with optical fiber was used for probe pin. This machine improved capabilities of CMM by the use of high resolution scales and optimized air bearings. CMM designed by Vermeulen [56] provided working space of 100 mm^3 and volumetric accuracy of less than 0.1 μm. In this machine, each of horizontal slides was provided with its own vertical support to avoid alternating gravitational load due to slide movement. This machine consisted of aerostatic bearings in all slides and three phase brushless linear motors in combination with digital pulse width modulated amplifier. In fact, Teague [57] built ultrahigh accuracy planar CMM at the National Institute of Standards and Technology (NIST) with capabilities to position and measure up to atomic scale accuracies over an area of 2500 mm^2. The machine provided point-to-point spatial resolution up to 0.1 nm and net uncertainty of 1.0 nm within measuring volume 50 mm $\times$ 50 mm $\times$ 100 μm. Kramar et al. [58] at NIST also designed and developed a measuring machine to meet measuring demands of future products such as nano-electronic devices, circuits, etc. This machine named as molecular measuring machine (M3) has been manufactured to measure up to 1 nm. Tactile sensor has been investigated by Cao et al. [59] to achieve measurement uncertainly less than 100 nm in measuring range of 25 mm $\times$ 25 mm $\times$ 13 mm. Dai et al. [60] has also developed CMM to meet the needs of micro- and nano scale dimensional metrology. Design information regarding key components of CMM such as positioning stage, probe and software, etc., can be found in this paper. Furthermore, 3D-AFM for 3D measurements of nano structures and an ultra precision micro/nano CMM based on Nano Measuring Machine (NMM) for 3D measurements of micro and millimeter size structures have been proposed by Dai et al. [61]. In this paper, authors applied vector approach probing (VAP) method to enhance measurement flexibility and minimize tip wear. Actually, two kind of tactile probes piezoresistive probe and ACP ball probe were utilized for measurements. One of the recent attempts in the field of micro-CMM has been made by Wu et al. [62] who have developed a CMM which can measure complex surface with resolution of 1 nm and measuring range of 25 mm $\times$ 25 mm $\times$ 5 mm. In this work, authors have used nano-CMM to test optical reflector with sine curve surface and identified fluctuation of topography as approximately 5 μm.

4 CMM advancements

The developments in CMM should be progressive in order to thrive in ever expanding competitive market. CMM should be more flexible, efficient and intelligent enough to meet fluctuating demands of customers. According to Zhang et al. [63], intelligent CMMs would most likely be successors of currently available CMMs. In their paper, they identified that intelligent CMM would be able to perform all functions automatically such as extraction of geometric and measuring information of part from its CAD file, selection of probe type, determination of measuring features, generation of number and coordinates of measuring points, etc. Intelligent planning environment for generating automated CMM inspection should be able to interpret and extract necessary design information available in CAD model, generate data structure for inspection plan and identify efficient inspection sequence [64]. Menq et al. [65] proposed an intelligent planning environment for automated dimensional inspection of complex sculptured surfaces. The system was made up of three basic components: CAD/CMM inspection planning module, CAD model based localization algorithm, and comparative analysis module in order to automate decision making in inspection planning.

There have been many other attempts as well in literature to develop methods and techniques that can allow CMMs work rather intelligently. One such attempt has been made by Fan and Leu [66], where CAD-directed inspection path planning system has been developed for CMMs. This system provided several characteristics such as automatic generation of evenly distributed touch points, detection of collisions, determination of collision free measurement path, etc. Another approach which has been proposed by Spyridi and Requicha [67] can automatically generate inspection plan for CMMs. The system is based on artificial intelligence (AI) and provides great flexibility in terms of part set up, accessibility analysis, probe orientation, number of features to be measured in one set up, etc. Fang et al. [68] proposed an integrated intelligent inspection system of stereo vision and CMM and successfully described its basic principle, structure and key technique. In order to save CMM running cost and programming time, Yuewei et al. [69] proposed a methodology which automatically generated an offline measurement program. Test results confirmed that proposed methodology was efficient resulted in saving about 30% time as compared to conventional method. Moreover, Spitz and Requicha [70] proposed a methodology based on heuristics to generate efficient collision free path for CMMs. Lu et al. [71] applied artificial neural network (ANN) as well as genetic algorithm (GA) to develop intelligent inspection plan for CMMs. Expert system proposed by ElMaraghy et al. [72] represents one of the significant efforts in the development of intelligent CMMs. This system consisted of all information regarding CMM characteristics, part functionality, its geometric properties and tolerances, feature accessibility analysis, inspection sequence, probe orientations etc which were required for automatic generation of inspection plan. This expert inspection planning system for CMM has been developed by incorporating several techniques such as pattern recognition technique, artificial intelligence, etc.

Multi-sensor or hybrid CMM provides combination of both contact and non-contact sensors on a single machine. It has ability to alter between probing devices without re-defining part coordinate system again and again. It has been widely accepted throughout manufacturing industries due its flexibility for 3D digitization. Shen et al. [73] developed an integrated system consisting of multiple-sensor (motorized probe and active vision) CMM, intelligent information module for sensor fusion and feature recognition and inspection planning module for surface digitization. In this system, active vision together with intelligent feature recognition algorithms provided global information including location and orientation, surface geometry and feature topology of unknown object. This information was then utilized to guide mechanical probe for high speed coordinate data acquisition. Evaluation of this highly automated and high speed 3D coordinate acquisition system provided satisfactory results in terms of both precision and feasibility. Similarly, Nashman et al. [74] integrated data from vision and touch sensors in order to improve working of CMM in dimensional inspection. In fact, this integrated system utilized strengths of one sensor to overcome limitations of other sensor. For instance, accuracy of touch probe and global information provided by vision system in short time simplified inspection task. Multi-sensor technology which combine tactile, laser scanning or vision systems can offer several benefits such as reduced measurement time, cost saving on fixture, minimum set ups, etc. These three technologies have distinct characteristics therefore their successful fusion on single CMM would result in wider range of applications. Their integration would provide high degree of flexibility in measurement operations enabling inspection of variety of parts on single machine. The greatest challenge for multi-sensor technology is integration of inhomogeneous data from different sensors with different resolution. However, issues associated with multi-sensor integration have successfully been overcome to take advantage of its numerous benefits. For instance, mixed system combining array of distance sensors and angle sensor by Schulz et al. [75] successfully measured large, flat and curved surfaces with very high lateral resolution. Moreover, Chan et al. [76] utilized multi-sensor approach for 3D digitization of complex parts in reverse engineering (RE). Yuhong et al. [77] also introduced a multiple-sensor CMM for data acquisition, intelligent information aggregation module for sensor fusion and feature recognition, and inspection planning module for surface digitization. In fact, recent developments and applications of hybrid contact and non-contact measuring systems for complex parts can be found in comprehensive review done by Li et al. [78]. A broad survey regarding multi-sensor data fusion in dimensional metrology has also been carried out by Weckenmann et al. [79]. They discussed innumerable concepts of multi-sensor technology in order to realize its benefits and importance in quality control, RE and many other industrial fields.

Virtual coordinate measuring machine (VCMMs) has primarily been developed to simulate measurement process for carrying out off-line programming, error analysis and uncertainty evaluation [80]. The concept of VCMM has successfully been implemented by Van Dorp et al. [81] to evaluate measurement uncertainty of CMM. Moreover, Yang and Chen [82] introduced a novel concept of haptic virtual CMM (HVCMM), where CMM's operation and its measurement process were simulated in virtual environment using haptic device. Haptic device provided several benefits such as force feedback and poisoning functions as well as built-in mechanism for collision detection to generate an efficient and user-friendly collision free inspection path. In another work, Wang et al. [83] utilized HVCMM to investigate accessibility of measuring probe in inspection process. Similarly, advanced virtual coordinate measuring machine (AVCMM) developed by Hu et al. [84] facilitated powerful simulation of CMM operations as well as evaluation of measurement uncertainty. Furthermore, it provided virtual environment to plan inspection strategy and perform virtual measurements in the absence of any physical machine. VCMMs have also been used to evaluate CMM machine errors by Tadahiko et al. [85]. Most often during probing, probe position get deviated as a result of structural deformation and change in air bearing gaps. Therefore, in this paper an error model based on finite element method (FEM) has been developed along with a virtual environment where deformation during CMM movement has been simulated virtually. Virtual CMM developed by Pahk et al. [86] can be used to predict volumetric errors in CMMs. In this research, comprehensive model has been used to compute volumetric errors using parametric errors of CMM and its probing system.

5 Conclusion

With increased demands of accuracy and precision from aerospace, automotive, medical, mold and die, semi-conductor, electronics, ship building and other manufacturing industries, it is mandatory to devise new procedures and machines capable of making complex measurements. CMM due to its high accuracy and repeatability of measurement results has been pioneer in inspection industries. However, CMM must provide required information regarding part dimensions and tolerances effectively and efficiently. There has been lot of advances in form of micro/nano CMMs, intelligent CMMs, virtual CMMs, etc., to keep pace with fluctuating market requirements. Moreover, it is critical for CMM users to understand and implement correct procedures and techniques to enhance reliability of measurement results. Performance evaluation of CMMs and determination of uncertainty associated with measurement results are crucial to maintain repeatability as well as reliability of CMM results.

This paper has successfully provided broad overview of different techniques for performance evaluation of CMMs in addition to various uncertainties associated with measurement results. Advanced concepts such as intelligent CMMs, multi-sensor CMMs, virtual CMMs, etc., have also been reviewed to highlight achievements and developments made in dimensional metrology. To meet increased demands of measurement for miniaturized components, researchers have been developing and improving CMM for better accuracy and repeatability in micro/nano ranges. Therefore, comprehensive review emphasizing CMM's progress to overcome challenges in measurement of micro and nano objects has also been presented. This review would give CMM users following information regarding:

- Methodologies and techniques to evaluate CMM performance.
- Measurement uncertainties for better reliability of CMM results.
- Understanding and awareness about advanced CMM concepts.
- Ways of how and when advanced CMMs should be utilized.
- Design, construction, accuracy and applicability of micro/nano CMMs.
- CMMs if properly utilized can solve most of current metrology issues.
- Motivation that CMMs can further be improved to suit specific needs of customers.

It can also be established that although CMMs have evolved continuously, still there is lot of scope for their improvement. For instance,

- Development of simple, efficient, easy to implement and standard procedures to compute CMMs measurement uncertainty.
- Optimization of CMMs for their operation in extreme environmental conditions.
- Introduction of simple and efficient methods for data fusion in case of multi-sensor CMMs.
- Design CMMs and software so that data between different CMMs can be exchanged successfully.
- Real time identification of CMM errors for instant feedback to improve measurement quality.

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