Laine Mears
Clemson University,
Clemson, SC 29634

John T. Roth
Penn State Erie,
Erie, PA 16563

Dragan Djurdjanovic
University of Texas,
Austin, TX 78713

Xiaoping Yang
Cummins Inc.,
Columbus, IN 47202

Thomas Kurfess
Clemson University,
Clemson, SC 29634

Quality and Inspection of Machining Operations: CMM Integration to the Machine Tool

Dimensional measurement feedback in manufacturing systems is critical in order to consistently produce quality parts. Considering this, methods and techniques by which to accomplish this feedback have been the focus of numerous studies in recent years. Moreover, with the rapid advances in computing technology, the complexity and computational overhead that can be feasibly incorporated in any developed technique have dramatically improved. Thus, techniques that would have been impractical for implementation just a few years ago can now be realistically applied. This rapid growth has resulted in a wealth of new capabilities for improving part and process quality and reliability. In this paper, overviews of recent advances that apply to machining are presented. More specifically, research publications pertaining to the use of coordinate measurement machines to improve the machining process are discussed. [DOI: 10.1115/1.3184085]

1 Introduction

Dimensional measurement as a feedback method to the manufacturing enterprise has traditionally lain in the realm of the long term, as metrology activities on thermally stabilized parts are carried out in a controlled temperature environment away from the manufacturing activity. Incorporating true dimensional *feedback* to the manufacturing process has necessitated a transition of the metrology activity from a highly controlled remote function to an environmentally robust measurement function tightly integrated to the manufacturing activity itself.

Since measurement systems and their integration with machining systems have evolved dramatically in recent years, the primary focus of this paper is on the use of coordinate measuring machines (CMMs) in conjunction with machining. The primary research barriers to enabling this integration are highlighted in Fig. 1.

These activities establish a framework of research progress that allows the identification of needs for the near future that will enable a transition of the metrology function to a more tightly integrated feedback solution for reducing manufacturing variation and improving process control. Recent work in these areas is covered in this paper, leading to commentary and recommendations for future research needs.

The remaining sections of this paper are subdivided into the following:

- off-line CMM use
- integration of the CMM with the machine tool
- advances in sensing technology
- inspection planning and efficiency
- advanced controller feedback schemes
- machine error compensation
- on-line calibration
- the use of simulation in measurement system planning

Finally, conclusions are made with recommendations regarding immediate and long-term research needs with respect to addressing issues of integration of the disparate measurement and machining functions.

Contributed by the Manufacturing Engineering Division of ASME for publication in the Journal of Manufacturing Science and Engineering. Manuscript received April 1, 2008; final manuscript received May 29, 2009; published online September 8, 2009. Review conducted by Kourosh Danai. Paper presented at the 2007 International Conference on Manufacturing Science and Engineering (MSEC 2007), Atlanta, GA, October 15–17, 2007.

2 Measurement Assessments for the Quality Control of Machining Systems

In their comprehensive review paper on machining process monitoring and control, Liang et al. address a number of part measurement systems for monitoring and process feedback. To that end, it is noted that vision systems and advanced image processing techniques, enabled by improved software capability, have become viable options for surface measurement metrology [1]. In addition, specialized types of in-process gauging allow for dimensional measurement at the micron level. However, generalized dimensional metrology, integrated to the machine tool, still needs to be addressed.

While not initially integrated to the machine tool, the coordinate measuring machine has been in use for decades as a versatile high-precision offline measurement device. As such, the CMM has the capability of generating multiple types of measures using a single sensor head. Moreover, a multitude of measures can be made on a single program without manual intervention, making the CMM highly efficient and allowing for the evaluation of a greater percentage, or even 100%, of manufactured parts. Though "inspecting in" of quality is not condoned in this paper, research into approaches for maximum inspection ability is important. However, as stated by DeStefani [2], the benefits of measurement and machining integration must be well understood before we "invade the process."

The CMM's versatility and efficiency has led to its more recent use as an on-line measurement device, particularly as an advanced feedback sensor for machining processes and their tooling. Considering the number of advances that have recently been made in this area, this section will only present a brief review of some notable accomplishments.

2.1 Coordinate Measuring Machines. In general, the coordinate measuring machine is used to digitize a measured part for the purpose of inspection or model creation (as in the reverse engineering process). A CMM has the capability of measuring in three dimensions, but is also widely used for two-dimensional (planar) or one-dimensional (linear) evaluations. The classical configuration of the machine is the Cartesian movable bridge de-

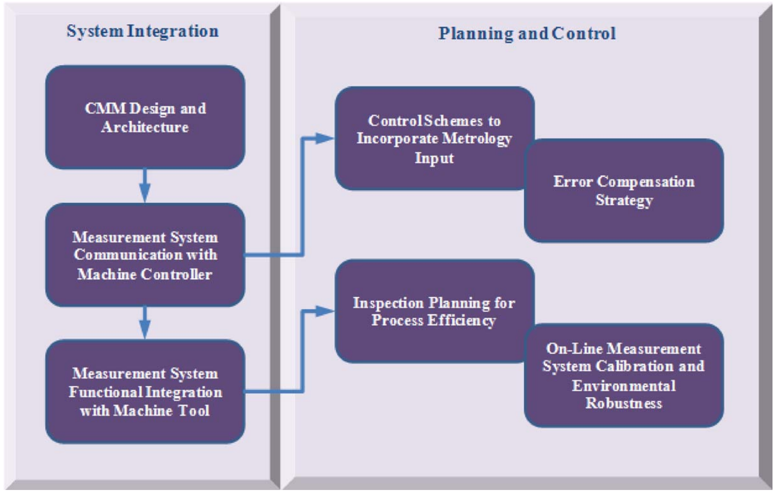

Fig. 1 Framework of research in measurement integration to machining. System integration issues between measurement and machining include functional and communication interoperability, as well as efficient planning for obtaining measurement data and its use in enhancing machine control.

sign, but some CMMs have been developed that utilize a cylindrical coordinate system for polar-specific artifact evaluation [3]. Additionally, recent developments have resulted in the design of a multijointed passive measurement device that, while requiring manual probe placement, allows greater freedom of motion and part accessibility [4]. In order to improve manufacturing efficiency, CMM operation has seen a recent evolution from a quality-based activity (driven by the organizational metrology function) to a manufacturing-based activity (driven by the operations function). This movement is beneficial in that the lag from production to evaluation is reduced and the overhead related to logistics and thermal stabilization is eliminated. This capability was enabled by recent advancements in automatic calibration and error compensation, allowing CMMs to operate in more harsh and/or temperature-variant environments.

Considering this, the next logical step is to integrate the CMM directly to the machine tool. Not only does this integration result in a further reduction in the processing-measurement lag, it also produces several other obvious advantages, including a known fixture state (the part does not need to be identified in space if the measurement device-fixture relationship is known) and the opportunity for immediate feedback to the machine controller. However, some issues emerge with the integration of inspection (or measurement) with value-added processing that should be addressed before such integration can become widespread. The first issue is the obvious loss of machine availability during the inspection, leading to a tradeoff between accuracy and inspection efficiency. This leads to the consideration that, if the part remains fixtured, if there is an opportunity to perform aligned machining activities during the inspection, or if this perceived disadvantage is outweighed by the previously stated benefits. The second issue is related to the reference plane for on-machine inspection. If the measurement platform is integral to the machine, the method for removing or compensating the machine geometric error from the measurement signal must be considered. Aside from the issues associated with the dislocation of the CMM from the controlled metrology lab atmosphere (e.g., temperature compensation), these are the major hurdles to overcome for successful integration of machining and inspection.

2.2 CMM Introduction to Machine Tool. As previously mentioned, the CMM can evaluate surfaces in one, two, or three dimensions using different coordinate systems, depending on the application and quality requirements. In addition, CMMs can generate single point data or scanned point clouds with fitting routines for characterizing part surfaces, and can measure any surface that can be reached by the probe [5]. The off-line CMM, as a quality evaluation tool, has been a manufacturing mainstay for decades. Originally designed as a modified machine tool, the CMM has been able to improve measurement accuracy and automation to a great degree [6]. However, the time lag between manufacture and off-line evaluation of a part leaves no room for direct process control. In fact, a number of defective parts can potentially be made during the wait for inspection.

In-line inspection using a CMM directly integrated with the machine tool allows for immediate inspection. Pancerella and Hazelton [7] asserted that on-machine inspection of components can reduce capital cost and reduce cycle time in a production environment because only one machine and process capability model is needed. On-machine acceptance further benefits the production cycle by promoting a design-for-inspectibility and concurrent engineering. Before switching to in-line inspection, however, it is vital to evaluate the integrated design on the basis of measurement time, quality objectives, design configuration, and integration with fixturing [8]. Such integration, coupled with the currently achievable measurement time and accuracy capability, enables 100% inspection and direct feedback to machine control or statistical process control (SPC) process evaluation [9,10].

In recent years several such integrations have been proposed. Kuang-Chao and Kuang-Pu [11] integrated a laser measurement probe directly with a computer-numerical control (CNC) machine in order to characterize freeform surfaces after machining. In this work, algorithms are developed for edge detection and the determination of shape error for on-machine mold manufacturing. In a similar work, Qiu et al. developed a spindle-referenced measurement device incorporated into a machining center for measuring 3D freeform contours with automatic following. The device is innovative in that it uses a combination of laser detector and linear encoder feedback to rapidly characterize surfaces and identify errors [12]. An additional integration development is a micromachining center adapted to be a measurement device by force feedback to the positioning servomotors [13]. The device is constructed from off-the-shelf parts and the achievable resolution is down to 5 nm. Shiou and Chen developed a process-intermittent measurement system for a milling center. The hybrid measurement system integrates a touch trigger probe with a triangulation laser probe system to measure regular geometric features and freeform surface profiles. Shiou and Chen used quadratic Bezier surfaces to approximate the measurement surface and to generate surface normals for inspection planning. The inspection system is verified with a CMM [14].

Wang et al. [15] described the error characterization of a free-form machined surface through separation of part form, part location, component movement, tool path variation, and fixture deviations from the nominal positions. Due to its multiple degrees of freedom and inherent ability to separate coordinate systems, an on-machine CMM is ideal for this decomposition analysis. Furthermore, with a CMM the primary error sources can be identified and corrected. Inspection strategy is also critical for on-machine probing. For example, Mou and Liu [16] used on-machine measurements (OMMs) of an artifact with known dimensions to complete a mathematical kinematic error model to improve accuracy of both on-machine inspection and machining. Mou and Donmez [17] proposed an inspection system that integrates on-machine and postprocess measurements to relate part errors to machine tool errors. Methods for improving the resulting geometric-thermal model are presented. Mou and Liu [18] employed state observation techniques to improve estimates of time varying machine tool errors. Mou and Liu furthered their work by developing a predictive search algorithm that increases the effectiveness and robustness of the error modeling method. The search algorithm is designed to determine the minimum number of points to measure for a given geometry [19].

However, machine reconfigurability becomes an important aspect of this process-inspection integration. The machining center must act as a material removal device in one instant (utilizing high force and controlled feed) then act as a measurement device the next instant (utilizing rapid traverse speeds and positioning accuracy). To address this new reconfigurability need, Wei et al. proposed a new programming framework designed to replace the traditional M- and G-code programming of CNCs. The software utilizes dynamic link libraries (DLLs) for rapid reconfiguration and is demonstrated on a three-axis milling machine [20].

2.3 Sensing Technology. The traditional CMM is fitted with a contacting touch probe that senses deflection magnitude and direction through orthogonal linear variable differential transformers (LVDTs). Integrating such a sensor into a machining system introduces issues such as probe wear and dynamic limitations. A number of approaches have recently been proposed to improve CMM sensing for efficiency and accuracy, enabling their use in production machining equipment.

Speed of measurements is one of the main potential benefits of on-machine measurement and significant efforts are placed on increasing this speed. Classical solutions include OMM of the workpiece using sensing probe [21] and replacing the on-machine touch trigger probe with a scanning probe to increase measurement speed as suggested in Ref. [22]. Though the precision of this system is lower than the precision of the existing CMMs, improved accuracy of the machine tool and a variety of precise noncontact sensors have made the system practical. In addition, numerous laser-based measuring devices recently became more and more available in OMM systems due to their high accuracy and increased speed compared with touch probes. Lee et al. [23] developed the OMM system with a laser displacement sensor for measuring form accuracy and surface roughness of the machined workpiece on the machine tool. Lee and Park [24] proposed an automatic laser scanner-based inspection planning algorithm for a part that has a Computer-Aided Design (CAD) model. Yoon et al. [25] combined the touch probe measuring devices and laser displacement sensor measuring devices into a 3D OMM system, which could predict the machining errors of each process much faster and accurately.

Cost is another consideration in sensor development for on-machine measurement. Liu et al. [26] developed an on-machine measurement system that enables the cutting tool itself to act as the contact probe. Setup time and machining accuracy improvements are realized at a fraction of the cost of traditional on-machine probing. Del Guerra and Coelho [27] developed a probe based on simple electrical contact to address the cost implementation barrier of OMM systems. The probe has 3 μm repeatability and addresses another traditional probe shortcoming, namely, the fact that a different force is required to actuate the probe in different directions, causing error due to pretravel distance. Probe pretravel and asymmetry error has also been addressed by Estler et al. [28] through compensation and demonstration in on-machine measurement applications [29].

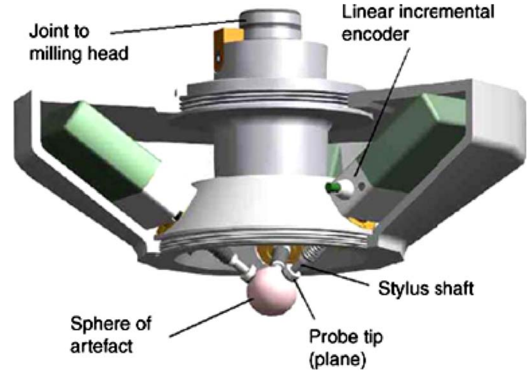

Fig. 2 Self-centering probe for rapid machine tool characterization [35]

Besides advances in sensing technology, one should note accuracy improvements achieved through software. One such work is reported by Choi et al. [30], who used OMMs to define a compensation method for reduction in the machining errors of a three-axis machine tool. High levels of OMM accuracy were achieved by including both probing errors of a touch probe and positioning errors of a machine tool that are being compensated to obtain the true machining errors for the repeated machining process. An actual simple cutting test was used to prove the efficacy of the compensation method. Yin and Lee [31] presented a software method in the frequency domain for evaluating workpiece straightness using on-machine probing. It reconstructs straightness profile for smooth, nonsmooth, periodic, and nonperiodic high frequency deviations, and has been applied to on-machine error correction [32]. More recently, Cedilnik et al. [33] generated a theoretical model of touch probe stylus ball error due to contact surface slope. Such representation lends itself well to compensation.

Advances in data processing and signal analysis capability have enabled the use of new sensing technologies for measurement. Noncontact laser sensors and analog scanning probes, which require highly accurate positioning performance, are now achievable in modern systems. To demonstrate this, Chang et al. [34] retrofitted a standalone CMM with improved motion control hardware, enabling the use of alternative sensors. Such technology could be readily incorporated into the integrated manufacturing-inspection system, improving measurement performance. To this end, Kuang-Chao and Kuang-Pu [11] demonstrated this novel sensor incorporation using an on-machine laser measurement probe.

Another improvement in sensing technology is presented in the work by Trapet et al. [35] where the authors have introduced a new design of self-centering probe specifically for machine tool use that gives an efficient and rapid technique to verify machine tool performance (shown in Fig. 2).

Higher machining degree of freedom exponentially complicates error analysis and compensation. For example, traditional error modeling approaches for three-axis CNC machine tools cannot be practically applied to five-axis machines. Lei and Hsu [36] addressed this deficiency through the development of a probe-ball device, which is used to directly measure position errors in five axes. The device is used in development of a least-squares error estimation algorithm in five axes [37]. The algorithm has been successfully applied to five-axis error compensation on the machine tool [38].

Interferometry has also been successfully applied to machining, in this case, with respect to manufacturing a concave mirror by Kohno et al. [39]. However, while stable and compact enough to be applied to in-process measurement, the interferometer has limited application to the generalized machining process due to prohibitively high cost and limitations on traverse speed.

An additional advancement in sensing technology was presented in the previously described hybrid optomechanical measurement machine (OMMM) of Sitnik. As discussed in this work, the OMMM takes advantage of the accuracy afforded a contact probe with the efficiency of an optical system [40]. Moreover, the OMMM is developed for the manufacture of large parts for the automotive industry and provides for automatic process control. Suzuki et al. [41] developed a new contact-based on-machine system for measuring small aspherical optic parts. The system incorporates a SIALON slider with low thermal expansion with a high-precision glass scale for feedback. Ultraprecision on-machine measurement is also addressed by Ohmori et al. [42] in their atomic-force microscope probe integration design; a repeatability of 5.6 nm is achieved. Additional recent work in on-machine sensor development is given by Jywe et al. [43] in the development of a new measuring system aimed specifically at error compensation. In this approach, position-sensitive detectors (PSDs) are developed with 1 μm repeatability, which have a small working range but high dynamic performance for improved characterization for fast machining. The sensors are demonstrated and used for compensation of 3D high-speed cutting, and shown to significantly decrease contouring error. Kobayashi et al. [44] developed a noncontact sensing system for profile measurement using a laser probe; the system achieves equivalent performance to current state-of-the-art high-performance measurement techniques.

2.4 Inspection Planning and Efficiency. Besides improvements in sensing technology, the speed and accuracy of OMMs are improved through a careful inspection planning process. In terms of inspection planning, one can discern two main directions in the recent advances.

- advances in individual feature-based methods for inspection planning
- advances in system-based methods for inspection planning

2.4.1 Individual Feature Based Methods. The key to strategic inspection planning at the feature-level are methods for evaluating errors in estimation of feature parameters due to a given inspection plan. Lee et al. [45] analyzed the measurement error sources existing in the OMM system. Cho and Seo [46] proposed the error modeling scheme using a closed-loop system of the OMM for the integration of CAD/computer aided manufacturing (CAM)/computer aided inspection (CAI). This strategy addressed inspection planning for the OMM process of sculptured surfaces through two significant factors: prediction of cutting error and consideration of cutter contact points in the measurement planning process to avoid error associated with cusps [46]. Davis et al. [47] proposed a direct memory access controller (DMAC), which closely related the CAD model, CAM system, and CMM system, and thus made it possible to utilize the measurement results from in-process inspection. Based on measurement error considerations, Yoon et al. [48] established an effective inspection system by using OMM system-based PC-NC, which optimally determined the number of measuring points, their location, and path using fuzzy logic and traveling salesman problem (TSP) algorithm. Xiong et al. [49] proposed a near-optimal probing strategy including two sequential optimization algorithms to incrementally increase the localization accuracy and a reliability analysis method to find a sample size that is sufficient to reduce the uncertainty of the localization error to a limited bound.

2.4.2 System Based Methods. Measurement selection for multistage machining systems (where the geometric relation between part and machine is broken at one or more points in the process flow) is addressed by Djurdjanovic and Ni [50,51]. In multistage systems, a large number of machining operations are performed across several stations, greatly increasing the complexity of inspection planning. To handle this complexity, heuristic or expert systems are frequently employed. However, in many cases these approaches result in a loss in inspection efficiency since redundant quality information is contained in the measurements. Through the stream-of-variation (SOV) analysis technique, a quantitative characterization of the generalized measurement scheme for multistation operations is employed for machining. Using SOV, the amount of quality information generated by a measurement set can be kept while minimizing the required inspection time. In a similar work, Gruget and Djurdjanovic [52] employed the method using a genetic algorithm (GA) approach to identify strongly correlated measurements and to create a scheme reduction plan to improve inspection efficiency.

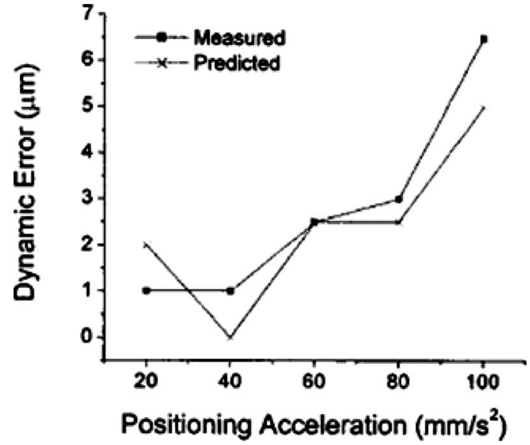

Fig. 3 CMM predicted dynamic error used in compensation [56]

2.4.3 Efficiency and Calibration. An immediate benefit of locating the CMM directly in the machining operation is the elimination of part transfer time and tracking logistics, and a subsequent capability to inspect a greater percentage of parts. However, some new issues also arise due to this situation, primarily: calibration of the measurement instrument, thermal influences on the measurement, and the inherent tradeoff between accuracy and measurement efficiency.

A principal disadvantage of machining and inspection integration is the logistic issues it introduces with respect to material flow through the machining process, most notably the loss of machine uptime during the part inspection. Therefore, the inspection planning process is critical for the successful integration of the CMM and the machine tool. Of most importance is the tradeoff analysis of measurement time versus accuracy (i.e., inspection efficiency). To address this issue, Vafaeesefat [53] gave a comprehensive inspection planning process for the CMM that produces an efficient inspection result for both simple and complex parts. Furthermore, to improve computational efficiency, Mu-Chen [54] presented planning approaches based in GAs for ideal surface fitting to the point cloud, and successfully demonstrated the approaches for sphericity evaluation. With a similar goal, Jiang and Chiu [55] presents a method for determining the ideal number of measurement points to evaluate part features for rapidly closing the CAI control loop. This methodology is automated for on-line applications.

Dong et al. [56] also addressed efficiency in their treatment of probe dynamic error modeling. In this work, a neural network approach is used to predict pitch and yaw error due to CMM acceleration. The results of one predictor are shown in Fig. 3. The

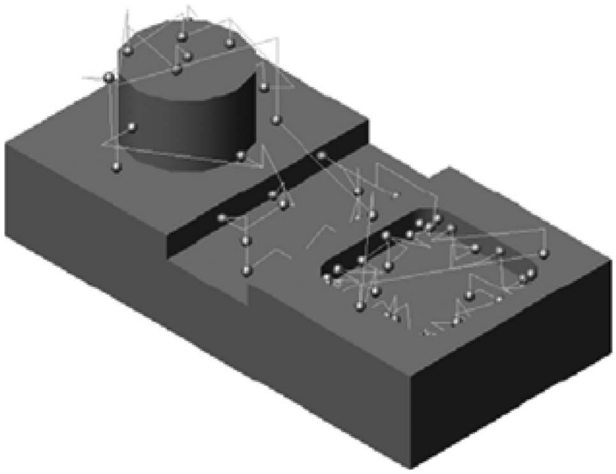

Fig. 4 Inspection path planning. The number of points, their location, and the inspection path are planned to minimize inspection time while maintaining acceptable accuracy [48].

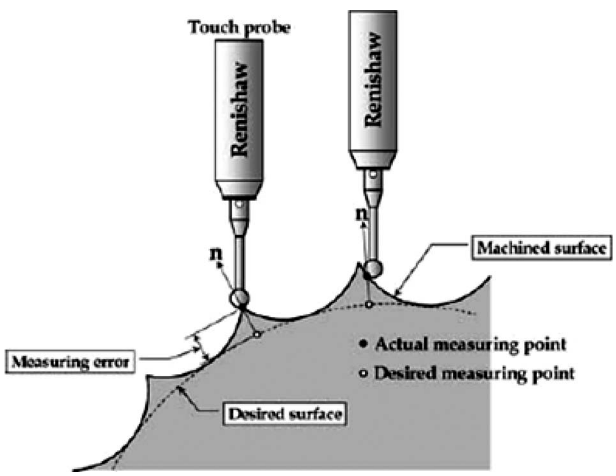

Fig. 5 Measurement error caused by machining cusp [46]

resultant compensation improves both accuracy and efficiency of measurement.

Using a different approach, Yoon et al. [48] described a PC-based on-machine measurement system efficient enough to perform 100% part inspection. Using part geometry information, the system determines an optimal number of measurement points using a fuzzy logic algorithm. The point locations are then identified by a modified Hammersley's approach to selection on geometric primitives. Finally, the inspection path plan is minimized through off-line solution to the TSP. Minimized-path point distribution on a sample part is shown in Fig. 4.

In a different approach to implementing the TSP, Cho and Seo [46] integrated CAD data to both machining and measurement planning and minimized probe travel distance through a revised implementation of the traveling salesman problem. The result is applied to a generalized sculptured surface characterization approach, which also explicitly addresses probe error due to the machining cusp, as shown in Fig. 5.

In another recent work that integrated CAD data, Jiancheng et al. [57] developed an autonomous coordinate measuring planning (ACMP) system based on the part's CAD model to enable true interactive operation between measurement and CNC machining (see Fig. 6).

The ACMP system not only links part geometry, machining programming, and measurement, but also autonomously optimizes the probe path plan and eases the measurement programming requirement, improving overall inspection efficiency. Ng and Hung [58] also presented a measurement planning system that derives the probe path directly from the CNC machining code. However, the plan presented by Ng and Hung does not require CAD model information as an input.

Starczak and Jakubiec [59] built a classification system for different measurement tasks and classified each task through a set of potential measurement strategies. The results are applied to a software system supporting optimal measurement strategy choice. In an alternative approach, Lin and Chen [60] presented an approach to optimal CMM path planning using a cut face method to avoid probe collision. The algorithm also addresses minimization of measuring points and the desire for normality of the probe to the surface being inspected.

Cho [61] proposed a feature-based inspection plan for targeting inspection efficiency. The plan occurs in two stages: a global stage to generate an optimum inspection path for all primitive features, then a local stage to decompose each feature and determine an

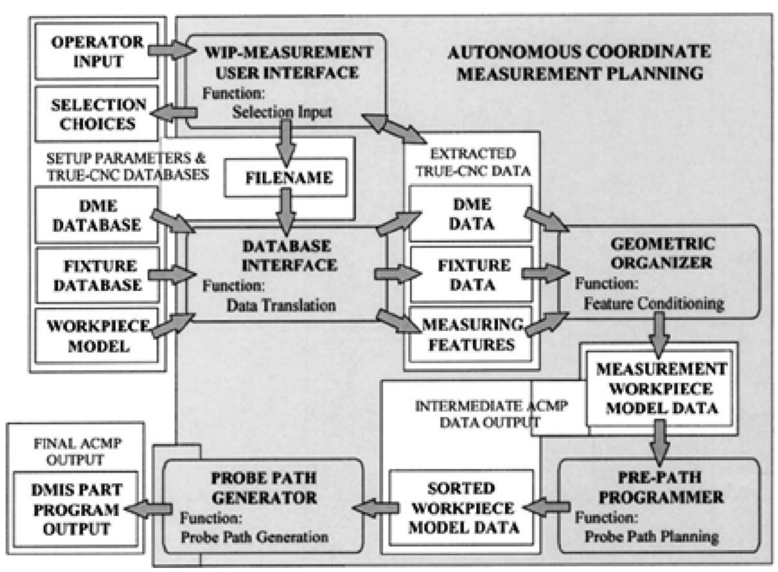

Fig. 6 Information flowchart of autonomous coordinate measuring planning (ACMP) system [57]

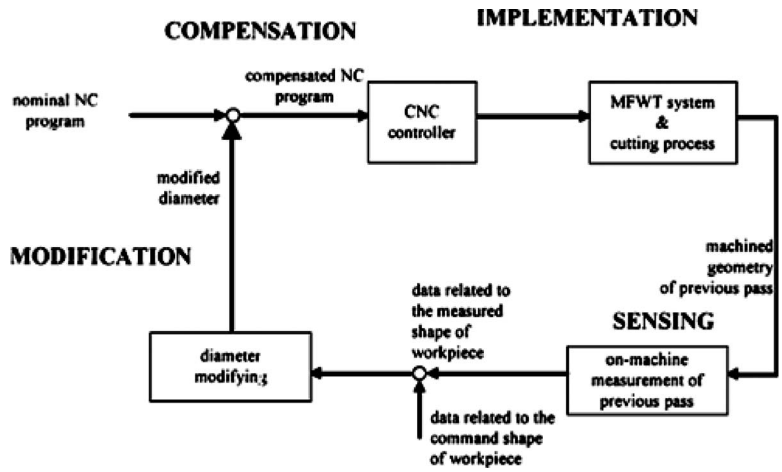

Fig. 7 Iterative error measurement and compensation system [63]

optimal number of sampling points based on the desired accuracy.

More recently, Sitnik [40] presented a hybrid on-machine inspection system utilizing both high-accuracy contact CMM and high-measurement-speed noncontact optical techniques. The approach is in four steps: an optical measurement inspection of the entire working surface, analysis of model parts noting critical areas, remeasurement of those critical areas using CMM techniques, and a final hybrid data analysis. The system also provides for automated feedback correction.

2.5 Advanced Controller Feedback. The CMM can be used not only as a device for tracking of part quality, but on a more fundamental level as feedback directly to the process for improving process control. Utilizing measurement information in real time to dynamically update manufacturing process has the potential of making parts with better dimensional accuracy. Two approaches have been reported. Sazedur Rahman et al. [62] developed an on-machine profile measurement system, the working principle of which was based on CMM and used a touch probe to measure the coordinates on the newly ground aspheric surface. The measured surface profile was used to guide wheel wear compensation. Davis et al. [47] took a separate approach: Instead of adding measurement equipment, they used the machine tool as a CMM. The machine tool could switch between a machining process and a measuring process. Machining error was generated by the CMM software and fed back to the CAD/CAM software for compensation. That the measurement requires the manufacturing process be stopped poses a major challenge for real production application in terms of dynamically updated manufacturing process for error compensation.

One benefit of direct three-dimensional coordinate feedback is the ability to provide control actuation not to individual axis actuators, but directly to the cutting tool position itself. Along this line, Liu [63] developed a diametral on-machine measurement and compensation system for multipass lathe operations as shown in Fig. 7. In this work, measurement and compensation in situ are able to achieve less than 2 μm error over 100 mm machined length.

On-machine probing information can also be employed with advanced controllers to improve systems performance. For example, Cho et al. [64] proposed a strategy for inspecting a sculpted surface using on-machine probing. The research integrates a CNC milling machine and inspection of 3D sculpted surfaces. The proposed methodology reduces inspection errors by moving the inspection points to reduce the error caused by the cusp shape. Cho and Seo [46] also recommended locating more inspection points in the region where the largest errors are more likely to occur and use the traveling salesperson problem algorithm (the TSP is a common problem in combinatorial optimization) to reduce inspection time. Choi et al. developed an on-machine measurement and error compensation system for a three-axis milling machine. A cube array artifact is proposed and measured using an on-machine probe in order to generate a model of machine positioning error. A test workpiece composed of two-dimensional curves was machined, measured using on-machine inspection, and then re-machined [30]. Choi et al. were able to reduce machining errors to less than 10 μm on the second cutting pass. Choi et al. employed a strategy for compensation similar to the strategy used by Lo and Hsiao [65], which is to apply the measured errors in the opposite direction to generate the compensation trajectory.

More recently, Kwon et al. [66] characterized closed-loop measurement error in CNC milling through a design of experiment (DOE) comparison between on-machine and off-line parts measurement. The results were demonstrated by a correcting feedback signal, with decreased measurement variation for more free-cutting material. Probe feedback is also applied to fixturing error by Wang et al. [15], whereby the influence of fixturing on the deviation between machined surface and defined tool path is quantified.

The movement of the CMM directly to the manufacturing floor has enabled its use for multidimensional statistical process control (SPC). SPC software specific to the CMM is surveyed by Franck and co-worker [9,67]. This technique is able to provide real-time multivariable monitoring and detection of process trends; application to limited process control is also addressed. SPC is enabled to evolve from a fixed-gauge single-variable activity to a fully-automated and flexible software-driven evaluation tool for process characterization.

The next logical step is to integrate the feeding of part measurement information to the machine for direct process control. This capability is enabled as the CMM and machine tool are integrated and the time lag between processing and evaluation is minimized. The work by Kwon et al. [66] investigates closed-loop error as it relates to integrated inspection; the authors demonstrated the efficiency and quality benefits of this information availability. However, a factor that needs to be addressed is the relative error between the machine base and the global base. Real-time feedback has been used successfully for position and dimensional control in a variety of processes such as grinding and is widespread in the industry [68–72]. However, more advanced control techniques have enabled capabilities such as force control, power control, and the direct control of subsurface damage [73,74].

2.6 Machine Error Compensation. Another inherent shortcoming of on-line inspection, besides potentially reduced process efficiency, is a reference error of the measurement. The fact that the machine reference frame is used as an input to the calibration

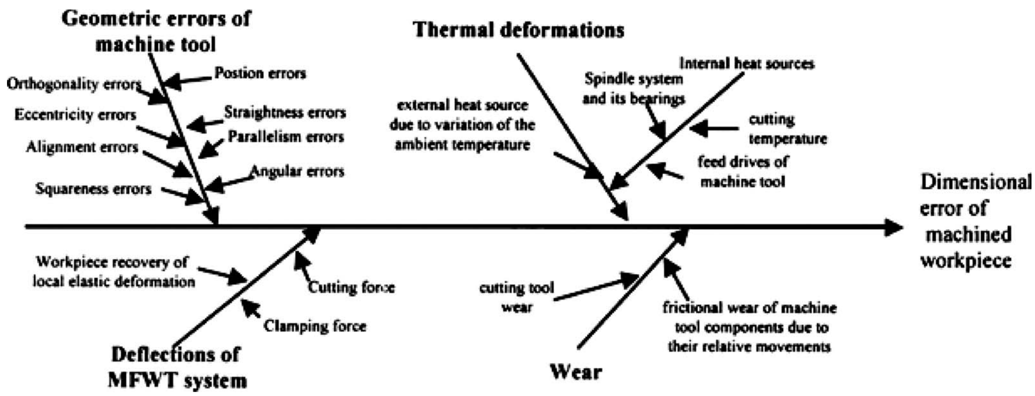

Fig. 8 Machined part error: geometry, force, thermal, and wear sources [63]

procedure introduces an inherent error (i.e., inclusion of the machine error in the measurement). This leads to a need to understand the error deviations in the machine as a result of the departure from the ideal kinematic model, and also the error behavior with absolute or processing time. The typical machine error sources, as described by Liu, are shown in Fig. 8. Therefore, any error compensation between the on-machine measurement system and the machined part must account for these sources: geometry deviations from ideal, system deflections due to force, thermal deformations, and longer-term dimensional deviations due to wear.

Recognizing this, Choi et al. [30] approached on-machine probing through a decoupling scheme whereby probe error components are modeled as polynomial functions, which include the machine error model with backlash. The workflow and compensation algorithms are given in Fig. 9. Here, model parameters are derived through the periodic measurement of a calibrated cube array artifact. In testing, this method achieved a reduction in the general machine error to less than 10 μm.

Error components, based on the machine rigid body kinematic model, are approximated using polynomial functions by Jung et al. [75]. The application improves the absolute error of in-machine touch probe measurement, which was reduced to 5 μm for a hemispherical test part. Moreover, Huang et al. [76] improved machine accuracy for a general 3D shape by 60% using similar techniques (eight-point interpolation method).

Smith et al. [77] described a calibration system using fiducial points for improving the accuracy of large monolithic machined structures. The described fiducial calibration system (FCS) negates the need for machine thermal analysis and geometric characterization by interferometric measurement. The method flow is given in Fig. 10. In another work employing the fiducial calibration system, Woody et al. applied the method to a large machine tool and characterized the uncertainty, enabling CMM-level accuracy on a shop floor machine tool without the need for individual error source determination [78].

An approach for calibrating thermally induced machining error using on-machine probing was proposed by Chen [79]. In this work, thermal errors were quantified and calibrated through artifact analysis by on-machine probing during cutting and exposed a shortcoming of thermal calibration by a simple air cutting experiment. Chen and Chiou [80] also correlated thermal error with temperature field during the actual cutting. Weck and Herbst [81] addressed thermal error through thermoelastic displacement calculation rather than cooling control; this approach uses a neural net to identify significant temperature probe locations for accurate thermal deflection characterization. A generalized thermal compensation model is proposed by Attia and Fraser [82], which seeks to resolve differences between direct measurement and indirect thermal modeling compensation methods. Yang and Lee [83] ad-

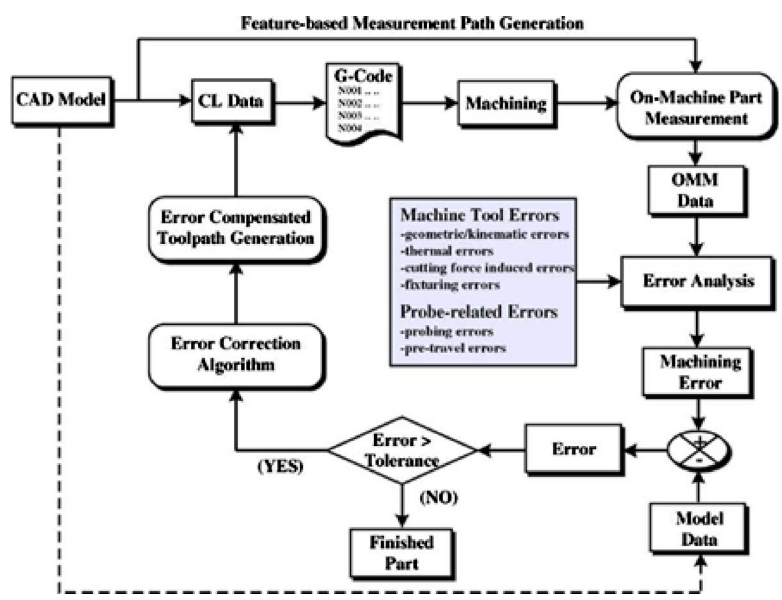

Fig. 9 Workflow for rapid on-machine probe calibration [30]

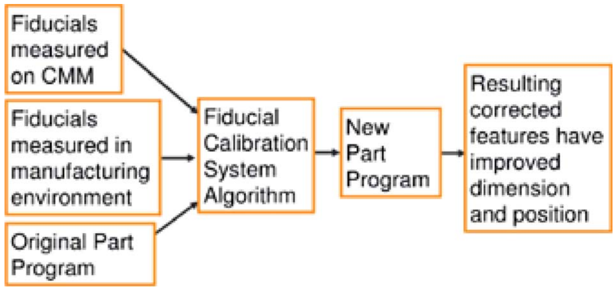

Fig. 10 Machine measurement and compensation using FCS [77]

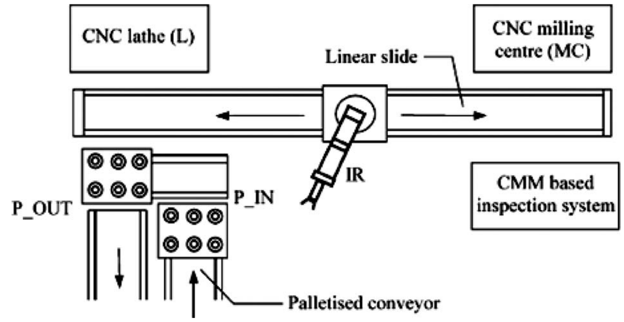

Fig. 11 Simulation of CMM integration to flexible machining line [102]

dressed measurement and prediction of thermal error using on-machine probing with two spherical artifacts. The method is incorporated with a neural network approach for compensation. Thermal error models and compensation are addressed through artifact methods by Kim and Chung [84], where thermal transients are effectively modeled. Kim and Chung [85] also addressed pure design of a 3D reference artifact for thermal error identification. In this approach, the thermal errors of cutting tool edge, axis expansion, and machine structural C-member distortion are addressed in a single calibration step; positioning error was reduced up to 75%. Yang et al. presented a thermal compensation method dynamic thermal error modeling (DTEM), which improves both accuracy and robustness of machine tool thermal deflection models [86]. Hysteresis effects are identified as the major factor of poor robustness of the current static modeling approach [87].

Direct thermal compensation is addressed by Wang et al. [87] using 17 different thermal error components. The system was implemented on a precision five-axis machining center, improving accuracy by 50%. Lei et al. [88] presented recent developments in efficient machine path representation through an enhancement to the nonuniform rational B-spline (NURBS) method. NURBS path length calculations are undertaken through subdivision of the path to avoid the necessity of iterative derivative taking posed by point-to-point path representation. The NURBS model has been most recently applied to fast error geometric compensation [89].

Model-free approaches have also been applied to error compensation. Tan et al. [90] addressed geometric error modeling and compensation using a different technique involving the application of a neural network (NN) approach. A machine error map is created using interferometric measurements, and the model is then applied to compensation through a learning algorithm. This form of error map is also readily applicable to the integrated inspection process [91]. Ziegert and Kalle [92] also used the NN approach to compute error mapping using on-machine probing. Shen and Moon [93] employed the NN approach to error correction of on-machine coordinate measurement. More recently, Cho et al. [64] extended the work of inspection planning for OMM to incorporate the obtained data in an error compensation algorithm. This approach addressed compensation of two machining error parameters through a polynomial neural network (PNN) approach, and effectively reduced machining error in end milling. Additional recent work is that of Fines and Agah [94] in positioning error compensation using a neural network approach. Three different artificial neural network (ANN) architectures were studied and demonstrated, and final compensation results were shown to be comparable to current state-of-the-art systems.

2.7 On-Line Calibration. A number of theoretical calibration tools and techniques have resulted from application of the CMM directly to the machining process. Moving the measurement process from the controlled metrology lab environment to the shop floor or even to the more environmentally harsh machining process introduces numerous environmental error sources. Contamination, temperature fluctuations, and the potential for physical contact all result in a need for increased and, therefore, more efficient calibration methods. The telescoping ball bar used for cylindrical machine tool error mapping is adapted to the inspection process by both Curran and Phelan [95] and Jiang and Chiu [55]. This "quick check" technique replaces artifact evaluation and allows for more frequent inspection.

Calibration of probe error is undertaken by Xiong and coworkers [96,97] through a new radius compensation method. Through this method, a dual optimization of compensation accuracy and computational time is achieved. The method is implemented in an automated machine tool setup system [98]. Srinivasan et al. [99] also addressed probe radius compensation specifically for freeform sculpted surfaces using OMM. This implementation uses real-time machined surface data rather than CAD model data generation.

On-line evaluation of measurement performance degradation due to harsh environmental factors is treated by Franceschini et al. [100]. This work proposes a rapid on-line diagnostic procedure integrated to the normal measurement cycle that identifies measurement error and monitors machine performance. The method does not require additional internal or external instrumentation.

2.8 Simulation of Measurement Systems. As with most processes, it is important to develop accurate simulation models that are able to recreate the actual response of the system; thereby allowing process parameters to be altered such that optimal conditions can be achieved through off-line analysis. To this end, Zhengyi and Yonghua [101] introduced a virtual coordinate measuring machine (VCMM) that utilizes haptic feedback from solid part models. This device is used to provide heuristic input and immediate validation and collision prediction for measurement path planning.

Simulation is also addressed, as it relates to shop floor flow planning by Siemiatkowski and Przybylski [102]. The simulated system is shown in Fig. 11. As a part of this work, two specific issues are noted with respect to the integration of a CMM to a flexible machining cell: job sequencing and inspection planning. Through the use of their simulation, the authors demonstrated that these issues have a major effect on the overall cell performance. Considering this, alternative flow strategies are presented to minimize sequencing and planning issues.

The virtual machining and measurement cell (VMMC) of Yao et al. [103] also simulates the machining and measuring process (on-line or off-line) and estimates the potential machining errors of a given part form. The traditional machining process development approach is contrasted with VMMC in Fig. 12. An example of the virtual measuring simulation is shown in Fig. 13.

The output of this model provides a basis for the optimization of both the machining process and integrated measurement planning. The ability of the authors to achieve this result "virtually" allows for improved part accuracy from the first cut as well as increased development agility with respect to varying market conditions. Kurfess [104] also presented additional advancements by

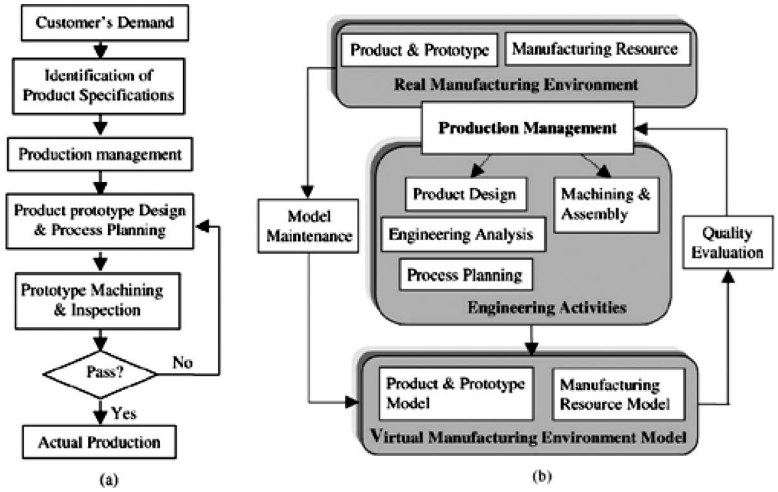

Fig. 12 Virtual machining and measurement cell architecture [103]. (*a*) Traditional development is time-consuming and expensive due to physical prototype iterations; (*b*) VMMC addresses optimization analytically to save time and cost.

the automotive manufacturing industry in inspection planning simulation, including solutions related to throughput and software control.

2.9 Trends and Impacts of Measurement System Integration. Fundamental issues relating to the integration of the CMM to a machining cell were treated by Wilson and Lenger [8]. The major considerations noted at the time were the following:

- identifying the true quality objectives of the inspection
- quantifying the part's configuration and critical attributes
- coupled integration of fixture design approaches
- process ownership by the implementation team

In order to successfully integrate measurement within the machining environment, these considerations should all be addressed through intense preplanning, prior to attempting any integration activities.

As noted, bringing together these two previously decoupled operations, machining and CMM measurement, has revealed a number of additional issues that are directly related to the integration into a common platform or manufacturing system. In this paper, several of these issues were highlighted, including efficiency of the inspection planning, error compensation and calibration, and the ability to feed back measurement data for direct machining control. These issues are in the forefront today, recognized as vital research areas that must be understood in order to allow for measurement integration on-machine tools. However, the next hurdle for true integration will be at the machine design phase. Shelton [6] noted in 1990 that developments in-machine tool technology should be coupled with corresponding technologies in CMM research. However, so far, these technologies have not been systematically developed, leading to some of the noted shortcomings.

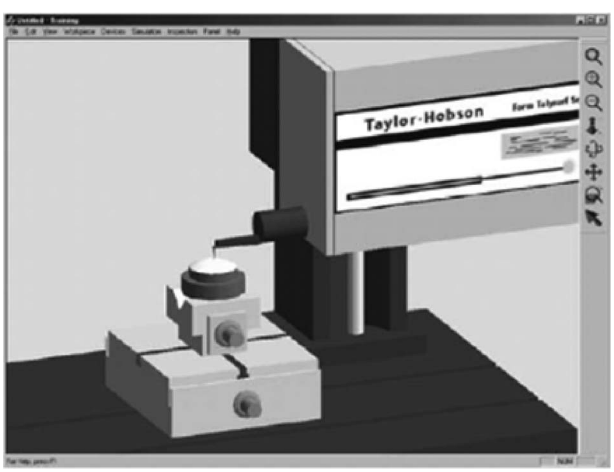

Fig. 13 Virtual measuring process of VMMC. Part measurement is simulated and the results are used to optimize the inspection efficiency.

One area later noted by Shelton and Ulbrich [105] that also remains to be adequately addressed relates to CMM data density and the diminishing accuracy returns on the time investment associated with inspection. To begin to address this, in their work, the "hyperactive woodpecker" CMM design approach is eschewed in favor of a more efficient and pragmatic approach to data analysis. This concept is also addressed by Weckenmann et al. [106] through the focus on the effect of measurement strategy planning on resultant measurement uncertainty, resulting in more efficient planning. Lin and Chen [60] addressed effective integration planning through an open architecture model using IDEF0 and STEP data models. The IDEF0 model is used to analyze measurement function requirements, while the STEP model is used to communicate measurement system commands.

Pahk et al. [107] proposed an interactive and integrated on-machine inspection planning system developed for machining and inspection planning of freeform mold geometry. The system outputs code for both CNC cutting and OMM commands for critical mold features. Limaiem and El-Maraghy [108] addressed development of robust inspection planning systems for optimum sequencing and resource allocation. This work accounts for physical probe size and attitude, and introduces the concept of *principal clusters*, groups of measurement points accessible by the given probe geometry. More recently, Oakham [109] highlighted on-machine geometric verification for process control strategies, incorporating on-machine measurement commands directly to the NC program. Quinn et al. [110] and Schuyler et al. [111] addressed communication issues between machining center and measurement system, developing a method to effectively pass information from measurement to controller for real-time error compensation. Kim and Chung [84] approached OMM integration through measurement error prediction and validation routines implemented directly in the CNC program, including the development of a set of G-code commands specific to measurement control as shown in Table 1.

However, to integrate these systems, it is also important to ad-

Table 1 Measuring G-codes [84]

Measuring features	Measuring G-codes with arguments
1. Probe start	G100 A. D□ H□ T□
2. Probe end	G100 A2.
3. Coordinate setting	G101 D□ W□
4. Environment setup	Ge102 E□ 1□ J□ K□ T□
5. Probe offset	G103 A1. B□ D□ E□ T□
6. Probe length	G103 A2. B□ E□ H□ T□
7. Machine tool calibration	G104 D□ E□ T□ W□ X□ Y□ Z□
8. Bore	G105 A1.D□ E□ R□ S□ U□ V□ W□ X□ Y□ Z□
9. Boss	G105 A2. D□ E□ R□ S□ U□ V□ W□ X□ Y□ Z□
10. Pocket	G106 A1. E□ H□ Q□ R□ S□ U□ V□ W□ X□ Y□ Z□
11. Web	G106. A2 E□ H□ Q□ R□ S□ U□ V□ W□ X□ Y□ Z□
12. Internal corner	G107 A1. E□ I□ J□ Q□ R□ S□ W□ X□ Y□ Z□
13. External corner	G107 A2. E□ I□ J□ Q□ R□ S□ W□ X□ Y□ Z□
14 Plane (X,Y,Z)	G108 E□ Q□ R□ S□ W□ X□ Y□ Z□
15. Bore-bore	G109 A1. C□ D□ E□ K□ U□ V□ X□ Y□
16. Bore-Ex. Cor.	G109 A2. C□ D□ E□ K□ U□ V□ X□ Y□
17. Pocket-pocket	G109 A3. C□ D□ E□ K□ U□ V□
18 Web-plane	G109 A4. C□ D□ E□ K□ U□ V□
19. Ex. Cor.-Ex. Cor.	G109 A5. C□ D□ E□ K□ U□ V□ X□ Y□
20. Plane-plane	G109 A6.C□ D□ E□ K□ U□ V□

dress error separation between the process and the measurement system. Along those lines, Knapp [112] stressed the need to comprehend error sources, especially the realization that both measurement uncertainty and measuring system setup and calibration are independent sources of error, but are not considered independently by measurement standards. This analysis is especially germane in the application of measurement in a harsh environment, outside of the near-perfect domain of traditional measurement system characterization.

Total system cost is another consideration for integration. Recent research on scale reduction in-machine tools (meso- and micromachining process development) introduces additional complexity to the integration process. As noted by Lee and Yang [113], installation of traditional interferometric equipment commonly used for machine tool characterization is difficult due to system size; miniaturized measurement components are also very expensive. To address this, they proposed a simultaneous characterization setup using capacitance sensing to reduce system cost. Dornfeld et al. [114] also cited development of more precise metrology methods as a "grand challenge" to further micromachining realization.

2.10 Future CMM Development Needs. There are current efforts underway to integrate CMM inspection directly with machining processes. The immediate benefits are reduced lag time between processing and inspection, and the application of on-machine inspection to multidimensional SPC and direct process feedback control (which are limited in availability when using traditional off-line CMM inspection).

However, a number of issues arise when integrating the CMM directly with the machine tool. Of particular importance are efficiency and throughput of the machining process after integration, and issues related to measurement error and calibration due to the inspection reference to the machine itself (machine errors also become integrated to the inspection). Additionally, environmental errors in the machine pose challenges for this development. These challenges are being addressed through simulation, error compensation, rapid calibration techniques, and incorporation of new sensing technologies.

3 Conclusions

This paper presents a review of the use of coordinate measuring machines in conjunction with machining. Included are advances in separate CMM designs, as well as integration of the measurement systems with machine tools and particular issues arising as a result of this integration. With the advent of more powerful processing capabilities, measurement technologies are becoming not only more efficient and accurate, but more accessible to the machine tool user as well.

The use of coordinate measuring machines in machining processes was reviewed; particularly the issue of integration of this technology as applied directly to the machine tool itself. The major points and recommendations are as follows:

- Coordinate measuring systems are accurate, highly flexible and widely used as off-line post-process evaluation tools. Recently, integration of such systems directly to the machine tool has been explored.
- There is a growing evolution of the CMM from a quality-based to a manufacturing-based activity, reducing production-measurement lag. This movement is enabled by new automatic calibration and temperature compensation routines.
- Integration of measurement directly to the machine tool is enabled by known geometric relationships to fixturing and allows for direct process feedback.
- Barriers to this integration include loss of machine availability during measurement and the inability to separate machine and part geometric errors.
- Measurement device calibration and the relation of measurement error to machine tool geometric error are primary concerns. Error compensation schemes and rapid on-line calibration routines are evaluated.
- Machine reconfigurability becomes an important aspect of process-inspection integration. The machining center must operate with high force and controlled feed for material removal, and rapid traverse speeds and accurate positioning for measurement. Control architectures have been proposed for this duality.

Overall, the fundamental issue with these measurement and monitoring technologies is proper integration of the measurement and material removal functions to result in an effective production system. As an example, Schuyler et al. [111] described the concept of a *smart machine tool system* that seamlessly integrates current process information with inexpensive and noninvasive sensors, and used models to automatically and continuously control the process; however, such an integrated system has yet to be realized.

Overall, the paper also highlights a number of issues which, if left unconsidered in the overall design, can result in inefficient or inaccurate results. Only through a systems approach to machine tool design can monitoring, measurement, and material removal functions be effectively integrated.

The demand for increased productivity and quality in conjunction with economic pressures necessitating cost reductions are driving the continuous evolution of machining processes. Integrated coordinate metrology systems are a key enabling technology for this task. Next generation systems will provide a number of advancements that are needed, such as the ability to operate in harsh environments (e.g., a coolant flooded machine tool). Furthermore, as networking and interfacing become more commonplace in the modern factory, these metrology tools will be even more integrated into overall production systems, providing real-time feedback for operations as well as long-term production trends. Finally one major issue will be overcome in the near future: the slow nature of coordinate inspection. The feed speeds of high-speed machining are significantly faster than those of CMM's or in-process inspection systems. Thus, these inspection systems must increase their throughput by increasing their measuring speeds. Next generation CMMs and probes (trigger, scanning and nontactile) will enable substantially increased speeds for inspection, rivaling those of modern high-speed machine tools. With these next generation capabilities, part quality will continue to increase without sacrificing productivity.

References

[1] Liang, S. Y., Hecker, R. L., and Landers, R. G., 2004, "Machining Process Monitoring and Control: The State-of-the-Art," ASME J. Manuf. Sci. Eng., **126**(2), pp. 297–310.
[2] Destefani, J., 2004, "On-Machine Probing," Manuf. Eng., **133**(5), pp. 51–57.
[3] Canon Communications, 2006, Medical Design and Manufacturing West, http://www.devicelink.com/expo/west07/exhibit/assembly.html
[4] Faro International USA, 2006, Platinum Arm Product Information, http://www.faro.com/content.aspx?ct=us&content=pro&item=2&subitem=2
[5] Kurfess, T. R., 2006, "What can CMMs do? They can Measure Almost Anything," Manuf. Eng., **136**(3), pp. 173–184.
[6] Shelton, R. S., 1990, "The Convergence of CMM and Machine Tool Design," Society of Manufacturing Engineers, Technical Report No. TP90PUB197.
[7] Pancerella, C. M., Hazelton, A. J., and Frost, H. R., 1995, "Autonomous Agent for On-Machine Acceptance of Machined Components," Proc. SPIE, **2596**, pp. 146–159.
[8] Wilson, J. O., and Lenger, S. S., 1985, "In-Line Inspection—The Integration of a CMM Into an FMS," Flexible Manufacturing Systems '85 Conference, Dallas, TX, March 11–14, pp. M585-155.
[9] Fix, S. L., and Franck, G. L., 1989, "Process Control: Emerging Role for CMM," Automation, **36**(4), pp. 30–32.
[10] Liao, Y. S., Chen, S. T., and Shih, P. Y., 2006, "Development of an On-Machine Micro Measuring Technique," J. Chin. Soc. Mech. Eng., **27**(5), pp. 599–604.
[11] Kuang-Chao, F., and Kuang-Pu, W., 1993, "Non-Contact Automatic Measurement of Free-Form Surface Profiles on CNC Machines," Proc. SPIE, **2101**(2), pp. 949–958.
[12] Qiu, H., Nisitani, H., Kubo, A., and Yue, Y., 2004, "Autonomous Form Measurement on Machining Centers for Free-Form Surfaces," Int. J. Mach. Tools Manuf., **44**(9), pp. 961–969.
[13] Neff, E., 2006, "A Micro Machining Center Applied as a CMM for 100% Inline Inspection," Society of Manufacturing Engineers, Technical Report No. TP06PUB131.
[14] Shiou, F.-J., and Chen, M.-J., 2003, "Intermittent Process Hybrid Measurement System on the Machining Centre," Int. J. Prod. Res., **41**(18), pp. 4403–4427.
[15] Wang, Y., Chen, X., and Gindy, N., 2005, "Fixturing Error Measurement and Analysis Using CMMs," J. Phys.: Conf. Ser., **13**, pp. 163–166.
[16] Mou, J., and Liu, C. R., 1992, "A Method for Enhancing the Accuracy of CNC Machine Tools for On-Machine Inspection," J. Manuf. Syst., **11**(4), pp. 229–237.
[17] Mou, J., and Donmez, M. A., 1993, "Integrated Inspection System for Improved Machine Performance," Proc. SPIE, **2063**, pp. 22–31.
[18] Mou, J., and Liu, C. R., 1995, "Adaptive Methodology for Machine Tool Error Correction," ASME J. Eng. Ind., **117**(3), pp. 389–399.
[19] Mou, J., and Liu, C. R., 1996, "Innovative Approach to Increase the Accuracy of Multi-Axis Machines for Process-Intermittent Inspection," ASME J. Manuf. Sci. Eng., **118**(4), pp. 585–594.
[20] Wei, L., Red, W. E., and Jensen, C. G., 2005, "An Open Device Driver Architecture for Direct Machining and Control," Computer-Aided Design and Applications, **2**(1–4), pp. 557–566.
[21] Keizo, U., 1994, "Die & Mold 3-Dimensional Measuring on the Machine," *Proceedings of the 4th Annual Conference on Die and Mold Technology*, pp. 208–209.
[22] Kim, S. H., and Kim, I. H., 1996, "The Development and Evaluation of OMM (On-the-Machine Measuring) System Using Scanning Probe," J. of the Korean Society of Precision Engineers, **13**(10), pp. 71–77.
[23] Lee, S. J., Kim, S. H., and Kim, O. H., 2003, "Geometric Accuracy Measurement of Machined Surface Using the OMM (On the Machine Measurement) System," J. of the Korean Society of Precision Engineers, **4**(4), pp. 57–62.
[24] Lee, K. H., and Park, H. P., 2000, "Automated Inspection Planning of Free-Form Shape Parts by Laser Scanning," Rob. Comput.-Integr. Manufact., **16**(1), pp. 201–210.
[25] Yoon, G.-S., Heo, Y.-M., Kim, G.-H., and Cho, M.-W., 2005, "Development of 3D-Based On-Machine Measurement Operating System," International Journal of Precision Engineering and Manufacturing, **6**(3), pp. 45–50.
[26] Liu, Z.-Q., Venuvinod, P. K., and Ostafiev, V. A., 1998, "On-Machine Measurement of Workpieces With the Cutting Tool," Integr. Manuf. Syst., **9**(3), pp. 168–172.
[27] Del Guerra, M., and Coelho, R. T., 2006, "Development of a Low Cost Touch Trigger Probe for CNC Lathes," J. Mater. Process. Technol., **179**(1–3), pp. 117–123.
[28] Estler, T. W., Phillips, S. D., Borchardt, B., Hopp, T., Witzgall, C., Levenson, M., Eberhardt, K., Mcclain, M., Shen, Y., and Zhang, X., 1996, "Error Compensation for CMM Touch Trigger Probes," Precis. Eng., **19**(2–3), pp. 85–97.
[29] Estler, W. T., Phillips, S. D., Borchardt, B., Hopp, T., Levenson, M., Eberhardt, K., Mcclain, M., Shen, Y., and Zhang, X., 1997, "Practical Aspects of Touch-Trigger Probe Error Compensation," Precis. Eng., **21**(1), pp. 1–17.
[30] Choi, J. P., Min, B. K., and Lee, S. J., 2004, "Reduction of Machining Errors of a Three-Axis Machine Tool by On-Machine Measurement and Error Compensation System," J. Mater. Process. Technol., **155–156**(1), pp. 2056–2064.
[31] Yin, Z.-Q., and Li, S.-Y., 2005, "Exact Straightness Reconstruction for On-Machine Measuring Precision Workpiece," Precis. Eng., **29**(4), pp. 456–466.
[32] Yin, Z.-Q., and Li, S.-Y., 2006, "High Accuracy Error Separation Technique for On-Machine Measuring Straightness," Precis. Eng., **30**(2), pp. 192–200.
[33] Cedilnik, M., Sokovic, M., and Kopac, J., 2007, "Scanning Errors Identification Using Touch Trigger Probe Head," International Journal of Computational Materials Science and Surface Engineering, **1**(3), pp. 275–291.
[34] Chang, D., Spence, A. D., Bigg, S., Heslip, J., and Peterson, J., 2001, "An Open Architecture CMM Motion Controller," Proc. SPIE, **4563**(1), pp 1–9.
[35] Trapet, E., Aguilar Martin, J.-J., Yague, J.-A., Spaan, H., and Zeleny, V., 2006, "Self-Centering Probes With Parallel Kinematics to Verify Machine-Tools," Precis. Eng., **30**(2), pp. 165–179.
[36] Lei, W. T., and Hsu, Y. Y., 2002, "Accuracy Test of Five-Axis CNC Machine Tool With 3D Probe-Ball. I. Design and Modeling," Int. J. Mach. Tools Manuf., **42**(10), pp. 1153–1162.
[37] Lei, W. T., and Hsu, Y. Y., 2002, "Accuracy Test of Five-Axis CNC Machine Tool With 3D Probe-Ball. II. Errors Estimation," Int. J. Mach. Tools Manuf., **42**(10), pp. 1163–1170.
[38] Lei, W. T., and Hsu, Y. Y., 2003, "Accuracy Enhancement of Five-Axis CNC Machines Through Real-Time Error Compensation," Int. J. Mach. Tools Manuf., **43**(9), pp. 871–877.
[39] Kohno, T., Matsumoto, D., Yazawa, T., and Uda, Y., 2000, "Radial Shearing Interferometer for In-Process Measurement of Diamond Turning," Opt. Eng., **39**(10), pp. 2696–2699.
[40] Sitnik, R., Sladek, J., Kupiec, M., Blaszczyk, P. M., and Kujawinska, M., 2006, "New Concept of Fast Hybrid Contact and No-Contact Measurement for Automotive Industry," Proc. SPIE, **6198**, p. 619803.
[41] Suzuki, H., Onishi, T., Moriwaki, T., Fukuta, M., and Sugawara, J., 2008, "Development of a 45° Tilted On-Machine Measuring System for Small Optical Parts," CIRP Ann., **57**(1), pp. 411–414.
[42] Ohmori, H., Watanabe, Y., Lin, W., Katahira, K., and Suzuki, T., 2005, "An Ultraprecision On-Machine Measurement System," Key Eng. Mater., **295–296**(1), pp. 375–380.
[43] Jywe, W. Y., Chou, C. T., Chen, C. J., Yang, T. Y., and Jwo, H. H., 2007, "Development of a Three-Dimensional Contouring Measuring System and Error Compensation Method for a CNC Machine Tool," Proc. Inst. Mech. Eng., Part B, **221**(B12), pp. 1755–1761.
[44] Kobayashi, R., Morita, S., Watanabe, Y., Uehara, Y., Lin, W., Mishima, T., and Ohmori, H., 2008, "Development and Evaluation of a Non-Contact On-Machine Profile Measurement System Using a Compact Laser Probe," Key Eng. Mater., **381–382**(1), pp. 187–190.
[45] Lee, S. J., Kim, S. H., and Kim, O. H., 1998, "The Analysis of Measuring Error in OMM System," J. of the Korean Society of Precision Engineers, **15**(5), pp. 34–42.
[46] Cho, M. W., and Seo, T. I., 2002, "Inspection Planning Strategy for the On-Machine Measurement Process Based on CAD/CAM/CAI Integration," Int. J. Adv. Manuf. Technol., **19**(8), pp. 607–617.
[47] Davis, T. A., Carlson, S., Red, W. E., Jensen, C. G., and Sipfle, K., 2006, "Flexible in-Process Inspection Through Direct Control," Measurement, **39**(1), pp. 57–72.
[48] Yoon, G.-S., Kim, G.-H., Cho, M.-W., and Seo, T.-I., 2004, "A Study of On-Machine Measurement for PC-NC System," International Journal of Precision Engineering and Manufacturing, **5**(1), pp. 607–617.
[49] Xiong, Z., Wang, M. Y., and Li, Z., 2004, "A Near-Optimal Probing Strategy for Workpiece Localization," IEEE Trans. Rob., **20**(4), pp. 668–676.
[50] Djurdjanovic, D., and Ni, J., 2004, "Measurement Scheme Synthesis in Multi-Station Machining Systems," ASME J. Manuf. Sci. Eng., **126**(1), pp. 178–188.
[51] Djurdjanovic, D., and Ni, J., 2006, "Stream-of-Variation (SoV)-Based Mea-

surement Scheme Analysis in Multistation Machining Systems," IEEE Trans. Autom. Sci. Eng., **3**(4), pp. 407–422.
[52] Gruget, T., and Djurdjanovic, D., 2004, "Optimal Reduction of Measurements in an Existing Manufacturing System," International Journal of Manufacturing Science and Production, **6**(3), pp. 103–117.
[53] Vafaeesefat, A., 2003, "Automatic CMM Inspection Planning System," International Journal of Industrial Engineering: Theory Applications and Practice, **10**(4), pp. 318–324.
[54] Chen, M.-C., 2002, "Analysis of Spherical Form Errors to Coordinate Measuring Machine Data," JSME Int. J., Ser. C, **45**(2), pp. 647–656.
[55] Jiang, B. C., and Chiu, S.-D., 2002, "Form Tolerance-Based Measurement Points Determination With CMM," J. Intell. Manuf., **13**(2), pp. 101–108.
[56] Dong, C., Zhang, C., Wang, B., and Zhang, G., 2002, "Prediction and Compensation of Dynamic Errors for Coordinate Measuring Machines," ASME J. Manuf. Sci. Eng., **124**(3), pp. 509–514.
[57] Liu, J., Ng, H., Yamazaki, K., and Nakanishi, K., 2003, "Autonomously Generative CMM Part Programming for In-Process Inspection," ASME J. Manuf. Sci. Eng., **125**(1), pp. 105–112.
[58] Ng, H., Liu, J., Yamazaki, K., Nakanishi, K., Tezuka, K., and Lee, S.-K., 1998, "Autonomous Coordinate Measurement Planning With Work-in-Progress Measurement for TRUE-CNC," CIRP Ann., **47**(1), pp. 455–458.
[59] Starczak, M., and Jakubiec, W., 2001, "Optimisation of Measuring Strategies in Coordinate Measuring Technique," *Proceedings of 3rd International Conference on Measurement*, Smolenice, Slovakia, pp. 179–182.
[60] Lin, Z.-C., and Chen, C.-C., 2001, "Collision-Free Path Planning for Coordinate Measurement Machine Probe," Int. J. Prod. Res., **39**(9), pp. 1969–1992.
[61] Cho, M.-W., Lee, H., Yoon, G.-S., and Choi, J., 2005, "A Feature-Based Inspection Planning System for Coordinate Measuring Machines," Int. J. Adv. Manuf. Technol., **26**(9–10), pp. 1078–1087.
[62] Sazedur Rahman, M., Saleh, T., Lim, H. S., Son, S. M., and Rahman, M., 2008, "Development of an On-Machine Profile Measurement System in ELID Grinding for Machining Aspheric Surface With Software Compensation," Int. J. Mach. Tools Manuf., **48**(7–8), pp. 887–95.
[63] Liu, Z.-Q., 1999, "Repetitive Measurement and Compensation to Improve Workpiece Machining Accuracy," Int. J. Adv. Manuf. Technol., **15**(2), pp. 85–89.
[64] Cho, M.-W., Kim, G.-H., Seo, T.-I., Hong, Y.-C., and Cheng, H. H., 2006, "Integrated Machining Error Compensation Method Using OMM Data and Modified PNN Algorithm," Int. J. Mach. Tools Manuf., **46**(12–13), pp. 1417–1427.
[65] Lo, C.-C., and Hsiao, C.-Y., 1998, "Method of Tool Path Compensation for Repeated Machining Process," Int. J. Mach. Tools Manuf., **38**(3), pp. 205–213.
[66] Kwon, Y., Tseng, T.-L., and Ertekin, Y., 2006, "Characterization of Closed-Loop Measurement Accuracy in Precision CNC Milling," Rob. Comput.-Integr. Manufact., **22**(4), pp. 288–296.
[67] Franck, G., 1990, "Using The CMM for Real-Time SPC," Technical Report No. MS900355.
[68] Osborne, J. R., 1993, "In-Process Gaging Improves Grinding Quality," Tooling & Production, **58**(12), p. 3.
[69] Knyazhitskii, A. I., Etingof, M. I., and Khasin, I. A., 1989, "New Range of Automatic Monitoring Instruments for Internal Grinding Machines," Meas. Tech., **32**(3), pp. 204–206.
[70] Gao, Y., and Jones, B., 1992, "Integrated Sensor System for Size and Roundness Control in Plunge Grinding," Int. J. Mach. Tools Manuf., **32**(3), pp. 281–290.
[71] Kaliszer, H., Webster, J., and Zhao, Y. W., 1986, "Dynamic Response of a Computer-Controlled In-Process Size and Roundness Measuring System," Technical Report No. IQ86-627.
[72] Scholz, R., 2002, "Gaging Improves Automatic Grinder Control," Quality, **41**(4), pp. 33–35.
[73] Nelson, L., Kurfess, T., Razavi, H. A., and Danyluk, S., 1999, "Generating and Modeling Subsurface Damage in grinding γ-Ti–48Al," American Society of Mechanical Engineers, Manufacturing Engineering Division, MED, *Proceedings of the ASME International Mechanical Engineering Congress and Exhibition*, 10(1), pp. 467–472.
[74] Razavi, H. A., Kurfess, T. R., and Danyluk, S., 2003, "Force Control Grinding of Gamma Titanium Aluminide," Int. J. Mach. Tools Manuf., **43**(2), pp. 185–191.
[75] Jung, J.-H., Choi, J.-P., and Lee, S.-J., 2006, "Machining Accuracy Enhancement by Compensating for Volumetric Errors of a Machine Tool and On-Machine Measurement," J. Mater. Process. Technol., **174**(1–3), pp. 56–66.
[76] Huang, P. S., Hu, Q., and Chiang, F.-P., 2003, "Error Compensation for a Three-Dimensional Shape Measurement System," Opt. Eng., **42**(2), pp. 482–486.
[77] Smith, S., Woody, B. A., and Miller, J. A., 2005, "Improving the Accuracy of Large Scale Monolithic Parts Using Fiducials," CIRP Ann., **54**(1), pp. 483–486.
[78] Woody, B. A., Smith, K. S., Hocken, R. J., and Miller, J. A., 2007, "A Technique for Enhancing Machine Tool Accuracy by Transferring the Metrology Reference From the Machine Tool to the Workpiece," ASME J. Manuf. Sci. Eng., **129**(3), pp. 636–643.
[79] Chen, J. S., 1997, "Fast Calibration and Modeling of Thermally-Induced Machine Tool Errors in Real Machining," Int. J. Mach. Tools Manuf., **37**(2), pp. 159–169.
[80] Chen, J. S., and Chiou, G., 1995, "Quick Testing and Modeling of Thermally-Induced Errors of CNC Machine Tools," Int. J. Mach. Tools Manuf., **35**(7), pp. 1063–1074.
[81] Weck, M., and Herbst, U., 1998, "Compensation of Thermal Errors in Machine Tools With a Minimum Number of Temperature Probes Based on Neural Networks," *Proceedings of the ASME Dynamic Systems and Control Division*, 64, pp. 423–430.
[82] Attia, M. H., and Fraser, S., 1999, "Generalized Modelling Methodology for Optimized Real-Time Compensation of Thermal Deformation of Machine Tools and CMM Structures," Int. J. Mach. Tools Manuf., **39**(6), pp. 1001–1016.
[83] Yang, M., and Lee, J., 1998, "Measurement and Prediction of Thermal Errors of a CNC Machining Center Using Two Spherical Balls," J. Mater. Process. Technol., **75**(1–3), pp. 180–189.
[84] Kim, K. D., and Chung, S. C., 2001, "Synthesis of the Measurement System on the Machine Tool," Int. J. Prod. Res., **39**(11), pp. 2475–2497.
[85] Kim, K.-D., and Chung, S.-C., 2004, "Synthesis of the 3D Artefact for Quick Identification of Thermal Errors in Machine Tools," Int. J. Prod. Res., **42**(6), pp. 1167–1187.
[86] Yang, H., and Ni, J., 2003, "Dynamic Modeling for Machine Tool Thermal Error Compensation," ASME J. Manuf. Sci. Eng., **125**(2), pp. 245–254.
[87] Wang, X., Shen, J., and Yang, J., 2008, "Precision Enhancement of Ucp710 5-Axis Machine Tool by Real Time Thermal Error Compensation," Key Eng. Mater., **375–376**(1), pp. 539–543.
[88] Lei, W. T., Sung, M. P., Lin, L. Y., and Huang, J. J., 2007, "Fast Real-Time NURBS Path Interpolation for CNC Machine Tools," Int. J. Mach. Tools Manuf., **47**(10), pp. 1530–1541.
[89] Lei, W. T., and Sung, M. P., 2008, "NURBS-Based Fast Geometric Error Compensation for CNC Machine Tools," Int. J. Mach. Tools Manuf., **48**(3–4), pp. 307–319.
[90] Tan, K. K., Huang, S. N., Lim, S. Y., Leow, Y. P., and Liaw, H. C., 2006, "Geometrical Error Modeling and Compensation Using Neural Networks," IEEE Trans. Syst. Man Cybern., Part C Appl. Rev., **36**(6), pp. 797–809.
[91] Zhang, G., Veale, R., Charlton, T., Borchardt, B., and Hocken, R., 1985, "Error Compensation of Coordinate Measuring Machines," CIRP Ann., **34**, pp. 445–448.
[92] Ziegert, J. C., and Kalle, P., 1994, "Error Compensation in Machine Tools: A Neural Network Approach," J. Intell. Manuf., **5**(3), pp. 143–151.
[93] Shen, Y., and Moon, S., 1996, "Error Compensation of Coordinate Measurements in Computer-Integrated Manufacturing Using Neural Networks," J. Mater. Process. Technol., **61**, pp. 12–17.
[94] Fines, J. M., and Agah, A., 2008, "Machine Tool Positioning Error Compensation Using Artificial Neural Networks," Eng. Applic. Artif. Intell., **21**(7), pp. 1013–1026.
[95] Curran, E., and Phelan, P., 2004, "Quick Check Error Verification of Coordinate Measuring Machines," J. Mater. Process. Technol., **155–156**(1–3), pp. 1207–1213.
[96] Xiong, Z. H., Chu, Y. X., Liu, G. F., and Li, Z. X., 2001, "Workpiece Localization and Computer Aided Setup System," *Proceedings of RSJ/IEEE International Conference on Intelligent Robots and Systems*, Oct. 29–Nove. 3, Maui, HI, 2, pp. 1141–1146.
[97] Xiong, Z. H., and Li, Z. X., 2001, "Error Compensation of Workpiece Localization," *Proceedings of IEEE International Conference on Robotics and Automation*, 3, pp. 2249–2254.
[98] Xiong, Z., and Zexiang, L., 2003, "Probe Radius Compensation of Workpiece Localization," ASME J. Manuf. Sci. Eng., **125**(1), pp. 100–104.
[99] Srinivasan, S., Kovvur, Y., and Anand, S., 2004, "Probe Radius Compensation for On-Machine Measurement of Sculptured Surfaces," *Proceedings of 2004 ASME International Mechanical Engineering Congress and Exposition*, Nov. 13–19, 15, pp. 913–920.
[100] Franceschini, F., Galetto, M., and Settineri, L., 2002, "On-Line Diagnostic Tools for CMM Performance," Int. J. Adv. Manuf. Technol., **19**(2), pp. 125–130.
[101] Zhengyi, Y., and Yonghua, C., 2005, "Inspection Path Generation in Haptic Virtual CMM," Computer-Aided Design and Applications, **2**(1–4), pp. 273–282.
[102] Siemiatkowski, M., and Przybylski, W., 2006, "Simulation Studies of Process Flow with In-Line Part Inspection in Machining Cells," J. Mater. Process. Technol., **171**(1), pp. 27–34.
[103] Yao, Y., Li, J., Lee, W. B., Cheung, C. F., and Yuan, Z., 2002, "VMMC: A Test-Bed for Machining," Comput. Ind., **47**(3), pp. 255–268.
[104] Kurfess, T. R., 2006, "CMMs are Key to Auto Quality—Measuring for Success," Manuf. Eng., **137**(3), pp. 131–140.
[105] Shelton, R. S., and Ulbrich, K. J., 1995, "Realities of Data Density and Its Effect on CMM Measurement," Technical Report No. 95082819899.
[106] Weckenmann, A., Knauer, M., and Kunzmann, H., 1998, "Influence of Measurement Strategy on the Uncertainty of CMM-Measurements," CIRP Ann., **47**(1), pp. 451–454.
[107] Pahk, H. J., Kim, Y. H., Hong, Y. S., and Kim, S. G., 1993, "Development of Computer-Aided Inspection System With CMM for Integrated Mold Manufacturing," CIRP Ann., **42**(1), pp. 557–560.
[108] Limaiem, A., and Elmaraghy, H. A., 2001, "Integrated Accessibility Analysis and Measurement Operations Sequencing for CMMs," J. Manuf. Syst., **20**(6), pp. 83–93.
[109] Oakham, M., 2007, "Automatic Set-Up," Engineer (London), **293**(7730), pp. 38–40.
[110] Qian, X., Ye, W., and Chen, X., 2008, "On-Machine Measurement for Touch-Trigger Probes and Its Error Compensation," Key Eng. Mater., **375–376**(1), pp. 558–563.

[111] Schuyler, C. K., Xu, M., Jerard, R. B., and Fussell, B. K., 2006, “Cutting Power Model-Sensor Integration for a Smart Machining System,” Trans. North Am. Manuf. Res. Inst. SME, **34**, pp. 47–54.
[112] Knapp, W., 2002, “Measurement Uncertainty and Machine Tool Testing,” CIRP Ann., **51**(1), pp. 459–462.
[113] Lee, J. H., and Yang, S. H., 2005, “Measurement of Geometric Errors in a Miniaturized Machine Tool Using Capacitance Sensors,” J. Mater. Process. Technol., **164-165**(1), pp. 1402–1409.
[114] Dornfeld, D., Min, S., and Takeuchi, Y., 2006, “Recent Advances in Mechanical Micromachining,” CIRP Ann., **55**(2), pp. 745–768.