Research Review of Coordinate Measuring Machines

ABSTRACT: The fourth industrial revolution driven by digitalization, networking and intelligence has put forward new requirements for Coordinate Measuring Machines, and two important development directions of Coordinate Measuring Machines are reviewed and analyzed in this paper. The first is the study of error compensation of Coordinate Measuring Machines (CMMs) including the study of dynamic and static error and the study of dynamic error compensation technology. Dynamic error compensation is particularly important in high-speed measurement. And how to ensure measurement accuracy in high-speed measurement is an important direction for the development of Coordinate Measuring Machines. The third is about the intelligence of Coordinate Measuring Machines which include CAD/CMM integration, independent decision-making, inspection planning, collision prevention and position recognition of the measured workpiece.

Keywords: Coordinate Measuring Machines; Static error ; Dynamic error; Error compensation; Autonomous decision; Inspection planning; Pose recognition;

1.Introduction

Coordinate Measuring Machines (CMMs), as a high-precision automated precision measuring instrument, have been widely used in machinery manufacturing, automotive, aerospace and other fields [1]. The first Coordinate Measuring Machine in the world was manufactured by Ferranti in 1956, and the first Coordinate Measuring Machine was successfully developed in 1976 in China, which opened a new era of development in the field of measurement [2]. With the rapid development of industrialization, modern industry has higher requirements for the precision and miniaturization of products, and how to further improve the measurement accuracy and measurement speed of Coordinate Measuring Machines has become a hot spot of research in the field of intelligent manufacturing at present.

With the rapid development of science and technology, advanced manufacturing technology and digital technology are becoming more and more closely related. Digitization technology is the digital definition, modeling, design, analysis, manufacturing and operation and maintenance of the product, and the most important part of the data is usually obtained directly from the product CAD model with the help of measurement, so the measurement of Coordinate Measuring Machines is essential. Coordinate Measuring Machines are enabling digital technology and are also developing in the direction of automation and intelligence, which is the need of modern industrial development.

2.CMMs error compensation technology research analysis

In measurement and scientific experiments, the existence of errors affects the accuracy. Coordinate Measuring Machines (CMMs) are composed of complex structures and diverse systems, so how to improve accuracy and reduce errors has become the core issue of CMMs development. To solve this problem is generally used error prevention method, the so-called error prevention method is to change from the source, mainly for mechanical equipment manufacturing materials or installation means, the purpose is to reduce the impact of external factors on the equipment, this method increases the manufacturing difficulty and cost of CMMs. The development of information technology and control theory provides a new way of thinking to reduce CMMs errors: error compensation. Compared with the error prevention method, error compensation is widely applicable, easy to use, and low cost, so it has received a lot of attention since the beginning of development.

CMMs crossed the second industrial revolution driven by electrification technology and experienced the third industrial revolution driven by automation technology. Along with the current fourth industrial revolution driven by intelligent technology, the direction of measurement technology has also changed, but improving measurement accuracy and efficiency is always the core problem to be solved in CMMs research.

2.1 Static error study analysis

Conventional CMMs are mostly used for static measurement, where measurement errors are generally caused by the constituent equipment components or the external environment [3], such as mechanical deformation of components or changes in the probe structure due to temperature. Static error compensation techniques are usually considered in terms of the constituent parts of the machine, and error compensation is performed by characterizing the manufactured parts. For errors due to thermal deformation the error compensation model is usually established using thermal deformation compensation techniques, while for error characteristics due to non-rigid effects the error compensation model can be determined by force-deformation analysis and modeling of the measurement mechanism components.

A lot of research has been carried out on static error compensation techniques, for example, Zurong Qiu et al [4] proposed to establish an error synthesis method by fusing the spatial errors generated by the measurement and the 21 geometric errors inherent to the CMMs through the study of the overall measurement characteristics of the CMM. Daodang Wang et al [5] analyzed the structural characteristics of the CMMs components at multiple levels and angles based on the measurement results of different poses in the same area on the rigid grid plate of the CMMs, proposed an error measurement algorithm based on the least squares algorithm, and concluded that the error could be effectively reduced by increasing the number of poses. P. Francoa and J.Jodarb [6] proposed a new index of equivalent error (EE) by analyzing the sources of CMMs errors, which represents the sum of geometric and dynamic errors related to CMMs performance, and by applying the EE-based model to the analysis of position, straightness, and part errors, respectively, it was demonstrated that the CMMs measurement results performed with The linear modeling accuracy is improved by 19.69%.

The probe of a CMM has a great influence on the measurement results, and the study of the probe has been a hot topic in error analysis [7]. Cai [8] conducted a detailed analysis of the pre-travel error sources of touch-trigger probes and found that the probe pre-travel and its anisotropy accounted for a large proportion of the error factors of the measurement system, based on which a probe pre-travel error correction model was established. Lee [9] developed a new five-degree-of-freedom carbon fiber plate force sensor probe by studying the characteristics of the probe components, which effectively eliminated the probe anisotropic sensitivity error and reduced the probe deformation and the actual contact point estimation error. Estler et al [10] studied a touch-trigger probe in detail and modeled and corrected for pre-travel errors. Dobosz and Wozniak [11] conducted a pre-travel analysis of a touch-trigger probe and analyzed the effect of various factors on the pre-travel of the probe through a three-dimensional model. Zhang Xinming et al [12] analyzed the pre-travel variation of the probe model to derive the factors affecting probe measurement accuracy, and further proposed a method for error compensation. Cui Xingxing et al

[13] studied the dynamic performance of CMMs in online inspection mode, constructed a dynamic error model of the pre-travel of the probe system, and verified the validity of the established prediction model by statistical analysis.

2.2 Dynamic error study analysis

With the development of modern industry, higher requirements are put forward for the use of CMMs. Static measurement is far from satisfying the demand, so dynamic measurement technology has been developed rapidly. Dynamic errors are caused in the dynamic measurement process, and the reasons for triggering measurement machine errors are more complicated because there are more uncontrollable factors in dynamic measurement. In the process of high-speed measurement, the impact of dynamic errors on the measurement accuracy is much greater than static errors. Due to the greater difficulty of dynamic error research and its late start, its research degree lags behind that of static error, but many scholars have also carried out research and analysis of the dynamic characteristics of CMMs.

In dynamic measurement of CMMs, the dynamic and static characteristics are disturbed by external factors thus generating dynamic errors, and the dynamic error value can be obtained by subtracting the dynamic measurement results from the real value [14]. The error between the actual and theoretical dynamic characteristics of the mechanism is the root cause of the dynamic error, so the study of dynamic error should start from the study of the dynamic characteristics of the mechanism. Nijs et al [15] constructed a vibration model by analyzing the dynamic characteristics of the measuring machine and proposed a method for the inherent frequency of the measuring machine structure to provide a reference for its design. Butler [16] analyzed the dynamic characteristics of the CMM probe and investigated the dynamic errors caused by the probe in detail. Weekers et al [17] considered the deflection occurring in the air-bearing guide in the CMMs as the main cause of the dynamic.Castro et al [18] calibrated the dynamic errors of CMMs using laser interferometry. Vermeulen et al [19] improved the dynamic performance of CMMs based on Abbe's principle by increasing the structural stiffness with constant CMMs mass. Calvo [20] improved the dynamic performance of CMMs by considering. Albert [21] used a laser tracker with higher accuracy to calibrate and calibrate the dynamic error of CMMs based on the study of dynamic error theory. Shedekar [22] found the repeatability of the dynamic error after removing the random error by analyzing the measurement data of the CMM, which provides a basis for dynamic error correction.Wang [23] analyzed the dynamic performance of the CMM in the online measurement process, separated the straightness error of the guide and the workpiece by using the error separation technique, studied the error influence factor and used the least squares method to improve the accuracy of the measuring machine. Yildiz et al [24] established a CMM dynamics model and validated it. Yildiz developed a dynamic model of CMMs and verified the validity of the model. The results of their study showed that the deformation of the connection mechanism and the motion deflection due to the limited stiffness of the air-bearing guide in the high-speed operation of the CMM are the main factors causing the dynamic errors of the CMM. Chensong Dong et al [25] analyzed the main reasons affecting the CMM error by studying the dynamic deflection angle error of the air-bearing guide. Pujun Bai et al [26] found that the influence of the corner error on the probe orientation during dynamic measurement was the key cause of dynamic error by using a laser tracker to measure the angle of the connecting part of the body. Chensong Dong et al [27] analyzed the dynamic characteristics of CMMs by laser interferometer and concluded that the additional inertia force caused by acceleration in dynamic measurement is an important cause of dynamic errors. Feng Zhong et al [28] analyzed the dynamic characteristics of CMMs during high-speed operation and established a prediction model based on gray-scale prediction theory to reduce the dynamic errors.

The probe is a very important part of CMMs, and there are two types of probes, touch-trigger and scanning, with different dynamic characteristics and different approaches to error handling. James [29] analyzed the characteristics of both types of probes and suggested that the scanning probe is preferred for high-speed measurement. Pereira [30] studied the characteristics of the scanning probe and constructed.Vliet [31] analyzed the connection between the impact force during measurement and the occurrence of probe bounce, and developed a probe model suitable for use in high-speed measurement. Ding [32] found that the error sources of the grating system and the probe system have a great influence on the dynamic performance of the measuring machine, and accordingly built a linear dynamic system model to describe the dynamic performance of the grating as well as the probe.

2.3 Research and analysis of dynamic error compensation technology

In line with the goal of low cost and high quality pursued by modern industry, cost-controllable error compensation techniques need to be sought to improve the accuracy level of CMMs. At present, the static error compensation technology is more mature, but the research on dynamic error compensation technology needs to be expanded.

The dynamic error of the CMM is caused by the measuring machine's own actual dynamic characteristics deviate from the ideal dynamic characteristics. Dynamic error compensation is to eliminate the effect of dynamic errors on the measurement results. The CMM dynamic error compensation technology initially relies on the experience gained from static error compensation, and there are two types of modeling methods. One type is the bottom-up modeling approach, which improves the dynamic accuracy by studying the dynamic characteristics of the measuring machine, analyzing its dynamic error formation principles, and then using mathematical reasoning to develop mathematical models for each mechanism that constitutes the machine [33]. The other type is the top-down modeling method, which does not only analyzes and builds a model for each error source in the dynamic measurement of the measuring machine, but also seeks the dynamic error law in the measurement results by analyzing and studying the measurement results, determines the factors affecting the dynamic error, and then uses information processing technology to obtain the mapping relationship between the dynamic error and the error factors so as to build a dynamic error compensation model.

Yetai Fei and Zhenying Xu [34,35] supported dynamic error correction by analyzing the motion characteristics of each component during dynamic measurement and applying wavelet analysis methods to decompose the error signals retroactively to external factors and each component part. Jizhu Liu et al [36] used the finite element method to analyze the force deformation of the CMM beam along the Z-direction under three load states of acceleration, deceleration and uniform speed, and established a dynamic error compensation model according to the analysis conclusion, and further derived the error compensation model under arbitrary load to achieve the effect of improving the measurement accuracy. Ligang Qu et al [37] proposed a finite element error compensation model from the perspective of the constituent components by considering the mechanical characteristics of the CMM. Hongtao Yang et al [38] designed error separation experiments combined with the application of partial least squares to obtain the main influencing factors affecting the measurement results, and constructed a spatial dynamic error model using support vector machines and dynamic error data, and proved that the method improved the modeling accuracy by comparison. Yi Lu et al [39] established a dynamic error model using BP neural network by analyzing the dynamic error sources of the measurement machine, which reduced the error value by 2.3 μm on average. Lei Zhao et al [40] analyzed the force state of the slide frame at different velocities on the Y-axis when the Z-axis was not moving with the help of SolidWorks Simulation and established a dynamic error compensation model, which was shown to reduce the error impact through experiments. Weihong Zhong et al [41] established a dynamic error prediction model based on RBF neural network by analyzing the motion state of CMM in the single-axis case, and the simulation showed that it has high prediction accuracy for the dynamic error of single-axis motion. Luo et al [42] found that the probe approach speed is a key influence factor on the dynamic performance of the measuring machine, and established a dynamic error compensation model accordingly, which effectively improved the measurement accuracy. Bulutsuz et al [43] considered the degree of influence of measurement points, measurement speed, measurement angle in XY plane, probe radius and approach distance on the dynamic error of the measuring machine, and used fuzzy logic to establish a dynamic error prediction model and validated it. error prediction model using fuzzy logic and verified its validity. Pinghua Ju et al [44] established a mathematical model for probe calibration by analyzing the factors influencing the measurement error of the online measurement system and its causes, and then obtained the probe radius compensation value, and the measurement accuracy of the compensated measurement system was significantly improved. Jingbin Guo et al [45] analyzed the degree of influence on measurement results by using probe measurements with different model parameters, and established a probe dynamic error model using fuzzy neural networks, and the results showed that the error could be reduced by more than 70% after compensation by the fuzzy neural network model.

3.CMMs intelligent technology

After decades of development, CMMs have become the main inspection equipment in the machinery manufacturing industry.But there are still some problems that need to be improved in the process, such as low measurement efficiency, boring measurement process and low accuracy of non-contact measurement. The intelligence of CMMs has also become a popular direction for its research application, including CAD/CMM integration, automatic decision making of measurement, inspection planning, anti-collision algorithm and position recognition of the measured object.

Nowadays, CAD/CAM integration technology is relatively mature, but research on CAD/CMM integration needs to be expanded. CAD/CMM integration is to use information from CAD to help CMMs to automatically perform inspection planning to generate control programs for measurement, so CAD/CMM integration research is an important direction for intelligent CMMs [46]. Bojamic [47] established a CAD/CAI integration system for integrated CAD/CAI system for complex surface measurement, and constructed an intelligent system for designing inspection paths, selecting probes, and measuring points by an expert system through feature modeling and artificial intelligence. Yang et al [48] and Tao et al [49] built a knowledge-based CAIP system to solve the problem of measuring complex rotary and 2½D parts, which can self-generate inspection path planning based on the part model and realize the integration with CNC-CMM through the DMIS (Dispatch Management Information System) processor. Integration with CNC-CMM through

DMIS processor. Xin Xu et al [50] developed an IGES post-processor for CAD/CMM integration by using IGES files as data exchange files. Jianmei Wang et al [51] proposed a scheme for automatic identification and detection of features using the unique identification of geometric elements in CAD models, which solved the problem of identifying information in CAD/CMM integration. Thoodore [52] constructed a measurement machine control system equipped with task decomposition techniques to perform measurement path planning using tolerance terms and measurement items extracted from a CAD database, and made a preliminary exploration of automatic CMM inspection. Eversheim and Auge [53] constructed an NCMES (Numerically Controlled Measuring and Evaluation) system to implement offline programming of CMM, and the NCMES system can automatically generate inspection programs based on CAD information and inspection planning.

Elmaraghy and Gu [54] built a CMM inspection planning system based on an expert system that extracts profiles and inspection tolerances from the model through part geometry modeling and syntactic pattern recognition. Furthermore, Gu [55] decomposed the inspection planning system into a series of modules covering knowledge, control operations, back-and-forth relationships, and linkage interfaces according to task division, and each module was responsible for the corresponding task. Yau et al [56,57] studied the path planning of CMMs and the anti-collision algorithm using heuristic hierarchical algorithms. Meng [58] developed and designed an intelligent system containing guided inspection, point detection, and automatic path planning for CMMs and CAD. Lin et al [59] built a system that obtains part information from a DXF file in CAD by a system that optimizes measurement by manually inputting measurement reference and measurement items and by dynamic programming. Han Zhao et al [60] proposed a CAD-based automatic CMM inspection planning system, which consists of data layer, service layer, function layer and interface layer from inside to outside, and the inner layer supports the operation of the outer layer through data and services. Fenghe Wu et al [61] proposed a hill-climbing genetic algorithm based on genetic algorithm to optimize the measurement path for CMMs in order to solve the convergence problem of traditional genetic algorithm in CMMs measurement path optimization, which effectively improves the local optimization ability as well as the convergence speed and helps to improve the measurement efficiency.

Applying machine vision technology to CMMs, and then achieving intelligent CMMs inspection by introducing CAD information and computer assistance is a popular research direction for CMMs intelligence. Jin Xie et al [62] developed a computer vision-based measurement system with mouse measurement and reconstruction by guiding the CMM surface measurement with image information acquired by CCD. Wangxian Zhang et al [63] obtained a measurement accuracy of 20 μm by combining stereo vision and non-contact measurement methods. Yufu Qu et al [64] fixed a camera on the Z-axis of a CMM and took photos of the surface of the object under test by moving the camera driven by the CMM, and used the focus evaluation function to determine the ortho-focus image thus launching the 3D coordinates of the points on the surface.

Shugui Liu et al [65] made the CMM successfully recognize the part poses by matching the actual image of the measured workpiece with the virtual image using image invariant moment and neural network image recognition algorithm. Fengshan Huang et al [66] established a monocular stereo vision recognition system based on CMMs panning, based on the principle of binocular stereo vision to make the CMM take two pictures at different points on the X or Y axis, respectively, to calculate the 3D coordinates of the measured part feature points in the camera coordinate system, and then use the camera calibration parameters, after transforming them into 3D coordinates in the machine coordinate system, and then combine them with the CAD ,Then the camera calibration parameters are converted into 3D coordinates in the machine coordinate system, and then combined with the corresponding coordinate data in CAD to find out the posture parameters of the measured workpiece. Qiangxian Huang et al [67] designed a vision-guided 3D nano probe based on the problem of approximation efficiency in the measurement process of micro and nano CMMs, and the probe was placed at a position 100 μm behind the focal plane of three cameras during measurement, and the high and low speed guidance of the table was realized by judging the distance between the measured workpiece and the probe through tools such as image processing and Gaussian filtering. Zhenhua Han et al [68] used the actual 3D data of the part to construct a combination corresponding to it in the virtual space, and by calculating the rotation translation matrix, the position identification was performed by comparing the similarity between the virtual image and the actual image data, and the method was obtained through experiments that the position error could be controlled within 1 mm. Based on the principle of machine vision, Chao Bi et al [69] combined vision measurement and CMMs measurement technology to solve the problem of measuring the three-dimensional features of air film holes.

4. Conclusion and outlook

This paper briefly analyzes two main application research directions of CMMs. Firstly, it outlines the current research status of dynamic error compensation technology of CMMs, that is to say improving measurement efficiency and accuracy is still an important direction of CMMs research, and then introduces the research progress of CMMs intelligence, including CAD/CMM integration, automatic decision making of measurement, detection planning, anti-collision algorithm and positional recognition of measured objects.

The fourth industrial revolution driven by digitization, networking and intelligence has put forward newer and higher requirements for CMMs, and the future development and application of CMMs mainly include: firstly, to ensure the measurement accuracy in high-speed measurement, the accelerated pace of production makes CMMs need to be used more in rapid measurement, and to ensure the measurement accuracy while improving the measurement efficiency, which can be done by using dynamic error compensation and improving the design structure of the measuring machine to improve the measurement performance of CMMs; the second is the transformation of the structural design of the measuring machine, mainly the choice of materials for the production of the measuring machine, for example, suitable lightweight materials can be selected to reduce the inertia force generated by the movement, and some hollow materials and synthetic materials will be widely used in the measuring machine in the future; the third is the development of intelligent CMMs, the current research for intelligent CMMs has made some achievements, the future in software development, vision application, measurement path planning, automatic decision making of measuring machine, fault diagnosis and other aspects need to be studied in depth, intelligent CMMs will be an important research direction for future development.

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