論文の内容の要旨

Thesis Summary

Image processing methods for dimensional metrology with industrial X-ray computed tomography

（産業用 X 線 CT 装置による寸法測定のための画像処理手法）

氏 名　　薛 林

With the fast development of computer digital technology such as CAD/CAM/CAE in manufacturing engineering, 3D scanning technologies related to the design and development of products have spread widely. Nowadays, coordinate measurement machines and laser probes, etc. are widely adopted as 3D scanning devices in industry. However, those traditional scanning devices can only capture outer surface information of a specimen, which is not suitable to the measurement of inside geometry and non-accessible part without damage. X-ray computed tomography (CT) is an advanced non-contact 3D scanning technology. Compared with traditional scanning devices, industrial CT (ICT) can non-destructively scan a specimen and can clearly, accurately, and intuitively display its inner structure, composition, texture, and damage, which provides a new way for the development of products.

Today X-ray CT finds applications in three major fields. CT scanner was in use in the medical field since the early 1970s [1]. Medical CT is the most common application of X-ray CT, which can produce cross-section images to assist medical diagnosis. Since 1980s CT was adopted by industry for material analysis and non-destructive testing (NDT) and evaluation [2]. In this application, CT is used to observe the characterization of materials (e.g. composites, polymers, metallic materials) and detect the defects of specimen (e.g. injection parts, castings, weldments). Recently, due to the ability to precisely measure inside and outside structure of a mechanical part in one single scan, CT has been introduced in the application field of dimensional metrology. It is a hot and challenging application for X-ray CT, in which CT is used as an alternative to traditional measurement devices (e.g. coordinate measurement machines, tactile probes, laser probes). So far, dimensional CT is the only device able to complete dimensional measurement of the inside geometry and non-accessible part of a component without damage. Also it can perform dimensional quality control and material quality control simultaneously [3].

Though the three application fields have a same theoretical foundation, they have a quite different requirement for CT scanner. In medical field, the X-ray power is limited to protect the people, and the people cannot be rotated in the scanning process. Moreover, the measurement accuracy of medical CT is relatively low. In contrast, in industry a sufficiently high X-ray power

is expected to penetrate the workpiece that is made of metal or has thick parts. Furthermore in dimensional metrology field, high measurement accuracy and low uncertainty are required. CT has been developed for several decades in medical and material fields and has a very high potential for dimensional metrology, but for CT metrology to reach maturity, much development work remains to be done [3]. This dissertation focuses on the study of dimensional metrology with industrial X-ray CT.

The main components of an ICT system are an X-ray source, a rotation table, and a 2D flat panel detector. The specimen is mounted on the rotation table, which is located between the X-ray source and the detector. First scanning parameters (e.g. voltage, current, magnification) are input to the CT system by a user. Then the X-ray source emits cone beam X-rays that penetrate the specimen and generate a 2D projection image known as a sinogram image on the detector. Typically the specimen is rotated 360° and usually more than 600 sinogram images are taken. Subsequently, on the basis of those sinogram images, a CT volumetric model is generated by use of the CT reconstruction algorithm such as the FDK algorithm [4] which is used in this dissertation. The voxels with reconstructed value (i.e. material attenuation coefficient or voxel value) in the CT volumetric model are called as CT volume data. Once the CT volume data is obtained, 3D polygonal meshes are computed by use of polygonization algorithm such as marching cubes algorithm [5]. The last step is evaluation of dimensional parameters.

In industry, dimensional metrology requires micron-level measurement accuracy. However, it is very difficult to achieve with CT due to various factors, such as data processing, beam hardening, X-ray scattering, user influence, partial volume, workpiece itself, etc. [6] [7]. Those influencing factors usually lead to some artefacts in CT reconstruction image. Some of typical artefacts in dimensional CT metrology are cone beam artefact, X-ray scattering, beam hardening, and spot size artefact. As circular scanning geometry cannot fully satisfy Tuy's data sufficiency condition [8], an exact reconstruction is possible only in the plane of the source trajectory, resulting in such cone beam artefact in the volumetric data. Beam hardening is a well-known cupping artefact, which is due to low energy photons of an X-ray beam with a range of energies attenuated more rapidly than high energy photons. Scattering is caused by deflection of X-ray inside the specimen or on the detector, which decreases the SNR locally. Spot size artefact is typically observed as blurring edge caused by the finite X-ray spot size, which cannot be avoided. In addition to those problems, the threshold method in the process of polygonal meshes computation is also a critical and difficult issue in dimensional CT metrology, as the current methods cannot detect edge accurately. Moreover, the user has a great influence on the CT measurement result. In the scanning process, first many scanning parameters that influence measurement quality are input to the CT system by a user, however, nowadays the values of those CT scanning parameters are typically evaluated by a user, resulting in a subjective measurement result.

In dimensional CT metrology, the influencing factors usually lead to some artefacts in CT volume data, which influence measurement quality. Reducing or avoiding those artefacts can improve CT measurement accuracy. For this purpose, three following approaches have been proposed in this dissertation.

We firstly present a method to analyze the CT reconstruction algorithm FDK (Feldkamp–Davis–Kress) effect independently from other kinds of artefacts by use of simulation, which can be observed in most of the common X-ray CT scanners with a cone beam. Based on this method, the FDK effect on the measurement accuracy of different kinds of specimens can be evaluated. By a numerical analysis of the FDK effect on measurement accuracy, deviation distribution feature and measurement error of different geometrical feature over the full range of spatial positions induced by the FDK effect are presented. Based on the deviation feature, an improvement strategy is proposed.

Then we study on CT scanning parameters evaluation for improving measurement accuracy. A new method is proposed to evaluate the quality of CT volume data for dimensional metrology. The method can aid CT metrology to achieve a high measurement accuracy by use of simulation. In the method entropy defined on the distribution of CT values in the image is used as a criterion. For entropy calculation of CT volume data, we give a detailed description about bin width and entropy zone. A common method for bin width calculation in histogram is selected in this study. For a local geometric feature of mechanical parts, concepts defined in geometric dimensioning and tolerancing (GD&T) are used as reference to define the entropy zone. And the size of the blurring area induced by the cone beam artefact is used as reference to determine the size of the entropy zone. The relationship between the entropy values of CT volume data and error parameters of CT metrology is shown and discussed. By use of this method, mainly we focus on specimen orientation evaluation, and some other typical scanning parameters are used to evaluate the proposed method.

Finally a new way for measuring the radius of a cylindrical surface that is a common geometric structure in mechanical parts is presented. The proposed method fits cylindrical surface from a projection image directly. By use of the new way, radius, unit vector of central axis, and one point on central axis can be estimated. Compared with a standard way for dimensional CT metrology, as CT reconstruction is excluded in the new way, the influence of some artefacts in the reconstruction image can be avoided, resulting in a higher measurement accuracy. And in the new way only dozens of projection images are used as input, which is far fewer than hundreds of projection images needed in the standard way, therefore the time and cost of CT measurement is reduced sufficiently.

The performance of the proposed methods is evaluated and demonstrated by use of simulation data and actual data. It is shown that it is possible to increase the accuracy of dimensional CT metrology by use of those methods.

Reference

[1] W. A. Calendar, 2006. X-ray Computed Tomography. Physics in Medicine and Biology 51:R29–43.

[2] P. Reimers, J. Goebbels, 1983. New Possibilities of Non-Destructive Evaluation by X-ray Computed Tomography. Materials Evaluation 41:732–737.

[3] J. P. Kruth, 2011. Computed tomography for dimensional metrology. CIRP Annals-Manufacturing Technology 60: 821–842.

[4] L. A. Feldkamp, 1984. Practical cone-beam algorithm. JOSA A, Vol. 1, Issue 6, pp. 612–619.
[5] W. E. Lorensen, 1987. Marching cubes: a high resolution 3D surface construction algorithm. Proc. ACM Siggraph, pp. 163-169.
[6] J. Hsieh. Computed Tomography: Principles, Design, Artifacts and Recent Advances. SPIE Press, 2 2003.
[7] Welkenhuyzen, F., 2009, "OPTIME. Industrial Computer Tomography for Dimensional Metrology: Overview of Influence Factors and Improvement Strategies," Antwerp, Belgium, May 25–26.
[8] H. K. Tuy. An inversion formula for cone-beam reconstruction. SIAM Journal on Applied Mathematics, vol. 43, no. 3, pp. 546–552, 1983.