Research on Mechanical Deviation Correction Method for Industrial CT

Jiayin Liu\textsuperscript{1,2}, Long Yang\textsuperscript{3} and Yuan Wu\textsuperscript{1,4}

\textsuperscript{1}DeepSea Precision Tech (Shenzhen) Co., Ltd, B3-4A1 Merchants Guangming Science Park, Shenzhen, Guangdong, China
\textsuperscript{2}School of Electronics and Electrical Engineering, Pusan National University, Korea
\textsuperscript{3}Product Management Department, iRay Technology, Shanghai, China
\textsuperscript{4}Digital Media & Systems Research Institute, University of Bradford, UK
Email: \{liujiayin, wuyuan\}@shenhaijingmi.com

Abstract. Industrial CT is the abbreviation of industrial computed tomography (CT) technology, which adopts X-ray imaging principle to realize the non-destructive three-dimensional imaging to obtain high-precision three-dimensional tomographic data and volume data inside the product, clear, accurate and intuitive. In addition, it can show the internal structure, composition, material and defective condition of the inspected object. Factors such as mechanical accuracy and mounting deviations can adversely affect CT imaging and, in severe cases, lead to CT imaging failure. It is important to achieve effective correction based on the existing CT mechanical accuracy and mounting deviations. In this paper, the authors collect data and performed experiments in a real CT system, they use standard test blocks to correct the deviations while keeping the existing CT system unchanged, the effectiveness can be validated by the experimental data.

1. Introduction
Industrial CT systems, as a new type of non-destructive testing equipment that allows threedimensional imaging of the inside of an object, provide an alternative three-dimensional imaging that the traditional two-dimensional real-time X-ray imaging inspection equipment does not have, including internal dimensions measurement, three-dimensional defect detection and other functions. Due to its special imaging principle and complex mechanical motion structure, a large number of experts and scholars over the world are interested in its mechanical deviation correction method, with constantly explored, various solutions have been developed in recent years. In this paper, a more simple and practical solution is given for the actual correction of industrial CT mechanical deviation through analysis and experiment. The research in this paper is innovative, mainly in the correction of deviation test block and its correction process to put forward unique insights, the authors hope it can bring some new ideas to the research and practice of industrial CT mechanical deviation correction in the industry.

2. Mechanical Deviation and Its Correction
Industrial CT is a non-destructive three-dimensional imaging device that uses X-rays to image the internal three-dimensional structure of an object, thus the accuracy of the imaging system is affected by the precision with which the mechanical platform operates and the mounting errors. Correction of the mechanical deviations is necessary to produce usable data, and the correction method and accuracy
determine the quality of the imaging. There are a number of correction methods, with the early focus on detecting and directly correcting mechanical deviations, which is straightforward, but operable poor, not only require multiple tools and test blocks to measure deviations, but also because of their limitations they are not able to detect and correct all deviations. Some methods have been developed to compensate the mechanical deviations by algorithms, but the detection of mechanical deviations is still done by the traditional methods. In recent years, some researchers have proposed the use of pure algorithms for the detection and correction of mechanical deviations, which are faster and more convenient than previous methods. Imaging results are also more accurate. These new methods generally require the design of a standard test block, and then propose an entire solution step by step based on that block, finally to complete the correction of the overall deviation. The researchers wanted to make deviation measurements as fast as possible with a well-designed test block and meanwhile complete deviation calibration, so the design of test block and the overall correction algorithms and solutions are the most critical and skillful.

There are many factors throughout the CT system that can lead to CT imaging artifacts, and numerous industry experts and scholars have long been dedicated to artifacts removal and practiced to ultimately improve the quality of CT imaging. A considerable amount of research has also been done with Refs. [1-3], focusing on the effects of mechanical bias on imaging, and some solutions have been proposed at the pure algorithmic level, and Refs. [4, 5] attempt to address the effects on imaging from a scattering and noise perspective, but it is not directly related to mechanical deviation correction, and Refs. [6-9] attempt to improve it from the perspective of 3D reconstruction algorithms to reduce artifacts, Refs. [10, 11] provide a quantitative assessment of the imaging and bias problem from the perspective of algorithmic simulation and data evaluation. There are few methods to measure and correct mechanical deviations directly based on standard test blocks in existing studies. The actual deviation of the CT system is measured by a standard test block, and input the deviation into the 3D reconstruction algorithms as an adjustment parameter. The imaging quality degradation caused by mechanical deviations can be solved by this method. Experiments have shown that this method is simple and effective. Some authors have attempted to eliminate artifacts without measuring mechanical bias, without solving the fundamental problem. There are many other factors that can cause artifacts, but the authors of this paper argue that the mechanical accuracy of a CT system is the most important, and that it can only be achieved with a good understanding of the accurate measurement and correction of mechanical deviations allows for more targeted follow-up of artifacts and other disturbances that may still exist.

3. Industrial CT Experimental Platform

3.1. Introduction to the Experimental Platform
All the experiments are based on a completed industrial CT system, its main internal mechanical motion structure design and real platform are shown in figure 1. The imaging chain includes a 160kV tube from VJ with a focal size of 0.8mm and an iRay X-ray flat panel detector with a 430mm x 430mm field of view. A 7-axis mechanical platform has a rotating stage with 0.005-degree resolution. Based on this experimental platform, we replaced the VJ tube with a higher-powered 225kV metal-ceramic tube from Gulmay, which has better CT imaging result for thicker objects that are difficult for the VJ tube to penetrate.

3.2. Test Specimens
The test in this paper is performed on classic and common aluminum die-cast parts, as shown in figure 2, from left to right: (a) Standard test block for correction, (b) physical test specimen (aluminum die-cast), (c) CT image before correction, (d) CT image after correction. We can see that the unclear text and symbol markings on the original specimen are sharpened by the correction, indicating that the correction is effective.
Figure 1. CT experimental platform: (a) structure design, (b) real platform.

Figure 2. Test on classic and common aluminum die-cast parts: (a) Standard test block for correction, (b) physical test specimen, (c) CT image before correction, (d) CT image after correction.

3.3. Mechanical Deflection Correction
The CT system in this paper has 7 axes, which is more difficult to correct than the simplest 2-4 axis CT system. According to the standard practice of the famous German CT manufacture - YXLON, for a standard 5-axis CT system it takes 2-3 workdays to correct mechanical deviations in the factory before the shipment to ensure its measurement accuracy. After the CT equipment is installed at the customer's site, the manufacturer needs to conduct a calibration. All mechanical corrections must be re-performed if moving, hitting, and disassembling any device during daily use. And the mechanical correction needs to be re-performed usually every 6 months to avoid new mechanical deviations caused by the wear of equipment and devices.

YXLON and other well-known CT equipment manufacturers have their own standard correction process, using their own designed test blocks, which is one of the key factor of major CT manufacturers to ensure the high precision of their CT systems. Among the mechanical deviations of all axes, the deviation of the vertical axis has the greatest influence on the image quality after CT reconstruction, which generally needs to be corrected first. The vertical axis, ensuring that it is perpendicular to the horizontal marble platform, and ensuring that the flat panel detector axis and the tube axis are parallel. In this work, the key steps for correcting the vertical axis are explained in detail. The corrections for the other axes are similar, but require a different standard test block. For the correction of the vertical axis, we use a test block as shown in figure 2a, which has the basic requirements: a 99.99% purity PC material as the supporting body, contains four 5 mm diameter lead balls; the PC body needs to be dug out in different depth to provide an accurate indication of the
radiation dose; PC body contains high precision machined metal test block made by aluminum-magnesium alloy (Stainless steel is required if correcting high energy CT systems).

Correction steps:
(a) Adjust the tube and FPD to the lowest height, with the farthest distance in the initial state.
(b) Use precise clamps to fix the standard test block to the center of the rotary table, ensuring that the ball plane is aligned with the focal point of the tube and the center of the FPD.
(c) Acquire two-dimensional images, rotate the turntable 90 degrees and acquire two-dimensional images again.
(d) Segment and locate the lead ball by algorithm, calculate the vertical axis deviation here by different coordinate points in the two images, noting it as ZD1.
(e) Raise the tube and flat plate to their maximum height, keeping the distance between them the same.
(f) Repeat (c) and (d), where the vertical axis deviation, noted as ZD2.
(g) The average of the two deviations yields the final deviation: \((ZD1+ZD2)/2\) in degrees.
(h) Importing this deviation value in the 3D reconstruction algorithm.

4. Experimental Data

Through the correction method introduced in the previous section, the 7 axes were corrected sequentially, and the CT imaging results were improved after each axis was corrected. In the case of the CT imaging of a component (70 mm diameter), wall thickness measurement and inner diameter measurement are carried out, and the error between CT and micrometer data is \(\pm 0.1-0.2\) mm, which can meet the accuracy requirements of the die-casting industry. A more accurate measuring grade CT must use a marble platform, to ensure rigidity, temperature and humidity stability, reduce the vibration. The CT system built in this paper is based on a metal pedestal platform, and the measurement error is also within the design specifications.

In the experimental session, we first corrected the vertical axis, then the other axes. Before correcting the final axis, we performed a CT scan test, which is almost ready for the CT reconstruction, but we can see that the detailed features of the object’s surface missing from the CT image, and artifacts can also be seen on the edges of the object from slice images. As shown in figure 3, a comparison of CT imaging and slice imaging before and after the mechanical deviation correction of the final axis shows that the correction to CT imaging quality improvement is great.

![Figure 3](image-url)

**Figure 3.** Comparison of CT imaging and slice imaging before and after mechanical deviation correction of the final axis: (a) pre-correction CT imaging, (b) pre-correction slice imaging, (c) post-correction CT imaging, and (d) post-correction slice imaging.
From figure 3, it can be seen that the slice image after correction clearly shows the font on the component surface, meaning that the image sensitivity of CT system is enhanced by the correction. In fact, it is difficult to show the font clearly on a 2D image by normal windowing operation method. We take 2D images of the same component by GE’s 2D real-time X-ray system, we can see the font with GE’s image enhancement technique “flash filter!”, but it is not as clear as our CT slice images.

We performed slice imaging at different locations of the part, and the result before and after correction is shown in figures 4 and 5, where the arrows indicate where the artifacts are located. The artifacts are caused by the two axes not being parallel, and by inputting the measured mechanical deviation into the 3D reconstruction software, the artifacts can be corrected and eliminated, avoiding both imaging and measurement errors.

Figure 4. Slice imaging of the same component at different locations, before and after correction, (a) pre-correction slice imaging with arrows indicating the location of artifacts, (b) post-correction slice imaging with no artifacts.

Figure 5. Slice imaging of the same component at different locations, before and after correction, (a) pre-correction slice imaging with arrows indicating where the artifacts are, (b) post-correction slice imaging, (c) CT imaging of the component.
5. Conclusion
With the increasing demand for quality management in the industrial production process, industrial CT has become a key factor in the quality control and quality assurance of manufacturing enterprises. An essential tool for production process improvement, it is currently the only equipment that can perform non-destructive 3D imaging inside the objects and is known in the industry as the best non-destructive testing methods. CT manufacturers need to correct their equipment before shipment and at the customer site, and may need to correct it during use, so a set of simple and effective correction tools and procedures become very important and are the unheralded skills of most famous CT manufacturers. The authors often use and debug CT equipment in their daily work, and summed up some experiences in this paper that the authors hope it can be used to promote or contribute the development and advancement of CT-related technology in industry.

In this paper, a set of standard test block is designed, a new mechanical deviation correction method is proposed, and the actual test is carried out on a real CT system, and the experimental results are analyzed and compared, showing that the correction method can effectively improve the CT imaging quality, and thus improve the slice imaging quality, CT system sensitivity and measurement accuracy.

Acknowledgments
This research was funded by Guangdong Province 2019-2020 International Science and Technology Cooperation Projects No.2020A0505100012: Research and Development of Key Technologies for Industry-oriented 3D Imaging.

References
[1] Wang Z B 2001 Effect of rotational center shift on image quality of CT reconstruction Journal of Military Engineering (3) 323-326.
[2] Liu X P 2006 Research on Cone-Beam Industrial CT Image Correction Technology (Northwestern Polytechnical University) pp 1-60.
[3] Zhang K D, Li Z and Zeng C 2012 Research on the Fast Implementation Method of Image rotation (Northwestern Polytechnical University) pp 51-56.
[4] Zhang F, Yan J and Li J X 2009 Review of industrial X-CT scattering correction techniques CT Theory and Application (4) 34-43.
[5] Hui M and Pan J X 2007 Simulation of three-dimensional cone-beam CT projection data Microcomputer Information (25) 248-249.
[6] Wang J D, Xia S R and Lu W X 1998 Evaluation of image reconstruction algorithms and error analysis Foreign Medicine (Biomedical Engineering) (6) 12-17.
[7] Wang J, Chen K Z and Tan H 2010 Study on the noise characteristics of industrial CT detection system Nuclear Electronics and Detection Technology (7) 929-934.
[8] Chen Z Q, Zeng K and Zhang L 2004 New advances in three-dimensional cone-beam CT imaging image reconstruction CT Theory and Applications (4) 5-8.
[9] Chen S and Chen H 2012 An industrial CT measurement accuracy evaluation methods Proceedings of the 2012 National Symposium on Digital Radiographic Imaging and New CT Technologies pp 189-197.
[10] Hui M and Pan J X 2007 Simulation of three-dimensional cone-beam CT projection data Microcomputer Information (25) 248-249.
[11] Cai Y F, Wang J and Yang D H 2002 Convolutional backprojection algorithm for the center of rotation deviation of CT scan Journal of Chongqing University (Natural Science Edition) (9) 55-58.