Neurocomputing 207 (2016) 335–345

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

# Locating of 2π-projection view and projection denoising under fast continuous rotation scanning mode of micro-CT

Min Yang [a,*], Jiawei Liu [a], Zhongchuan Li [a], Lihong Liang [b], Xiaolong Wang [c], Zhiguo Gui [d,*]

[a] School of Mechanical Engineering and Automation, Beijing University of Aeronautics and Astronautics, Beijing 100191, China
[b] China Special Equipment Inspection and Research Institute, Beijing 100013, China
[c] Shanghai Volkswagen Automotive Company Limited, Shanghai 201805, China
[d] National Key Laboratory for Electronic Measurement Technology, North University of China, Taiyuan 030051, China

ARTICLE INFO

*Article history:*
Received 30 October 2014
Received in revised form
25 March 2015
Accepted 4 May 2016
Communicated by Luming Zhang
Available online 17 May 2016

*Keywords:*
Micro-CT
Projection sequence data
Fast continuous rotation scanning
Image denoising
Structure similarity

ABSTRACT

The fast continuous rotation scanning mode is suitable for situations when a higher scanning speed or a lower radiation dose is required for micro-CT. Under this scanning mode, the specimen rotates far beyond 2π, but not an integral multiple of 2π continuously while the detector collects projection images at a high frame frequency, which consequently produces uneven-distributed and redundant projections with a high level of noise. Therefore, for subsequent three-dimensional (3D) image reconstruction, each 2π-projection view during a whole rotation span must be accurately located, and image denoising is an essential pre-processing step for improving quality of reconstructed images. For matching the rotation angle with the projection image accurately under the fast continuous rotation scanning mode, a structure similarity (SSIM) coefficient was used as a control parameter for extraction of periodic projection sequences for 3D reconstruction. Meanwhile, an improved non-local means (NL-means) algorithm was proposed for noise reduction in projection sequences, and a graphic processing unit (GPU) capable of highly parallel and fast floating-point calculation was used for alleviating the computation cost of the algorithm. The experimental results show that the SSIM-based 2π-projection-view locating method is highly accurate in identifying periodic projection sequences and is easy to implement, and that the improved NL-means algorithm can well restrain the quantum noise while preserving detailed information.


## 1. Introduction

Micro computed tomography (micro-CT) is a useful pre-clinical imaging modality that can yield accurate information on small-animal organ anatomy in a minimally invasive way. Compared with conventional cone-beam CT, a micro-CT system employing a micro-focus X-ray source and a high- resolution flat-panel detector can provide micrometer-level spatial resolution [1–7]. Illustrated in Fig. 1 is a schematic diagram of a typical micro-CT system. The cone-beam X-ray penetrating the specimen is collected by a flat-panel detector. While the specimen fixed on a rotary stage spins around the rotation axis, the flat-panel detector collects digital radiography (DR) projections of the specimen at different angular views over 360°. After all DR projections are acquired, a 3D reconstruction is performed that yields the volume image. The host PC is responsible for the unified control of the secondary control terminals such as the X-ray source, rotary motor, and detector via interactive communication.

Although the typical level of the radiation dose used by current micro-CT systems is generally not lethal to the animal, it cannot be sufficiently high for inducing changes in the immune response and other biological pathways, which may alter the experimental outcome. On the other hand, the scanning speed is another satisfied factor impacting the micro-CT image quality, because internal motion due to physiologic processes such as cardio-pulmonary motion can result in significant, obscuring image artifacts. Therefore, fast scanning with a low dose is a challenging task for current commercial micro-CT systems.

The fast continuous rotation scanning mode is suitable for situations when a higher scanning speed or a lower radiation dose is required, such as visualization of interior dynamic changes in the specimens scanned during the course of the loading process for industrial applications, or in-vivo imaging of live subjects for pre-clinical applications [8–11]. The specimen rotates continuously while the detector collects projection images at a high frame frequency. Because of the high frame frequency and small detecting unit size of the detector, a low X-ray exposure is yielded and DR images with high-level noise are produced, which impose an inherent limitation on micro-CTs. Thus, in the pre-processing step

* Corresponding authors.
*E-mail addresses:* minyang.ndt@263.net, yangminbuaa@163.com (M. Yang), guizhiguo@nuc.edu.cn (Z. Gui).

http://dx.doi.org/10.1016/j.neucom.2016.05.018
0925-2312/

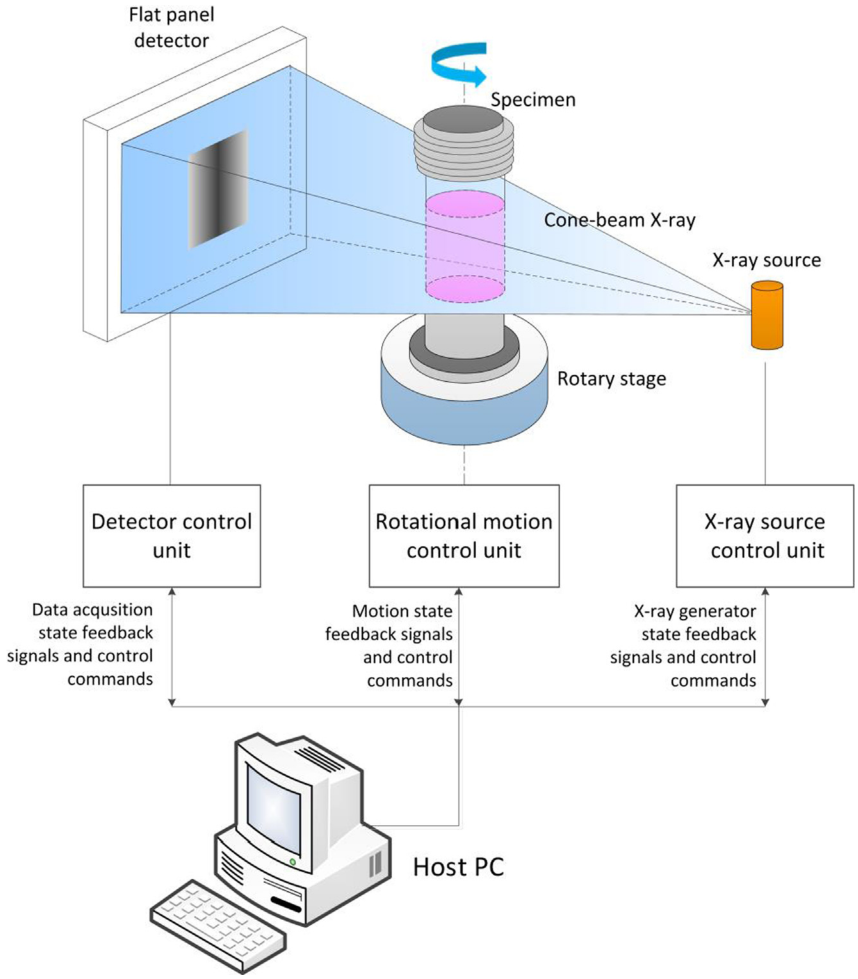


**Fig. 1.** Schematic diagram of a micro-CT scanning system.

of CT reconstruction, noise reduction is essential for improvement of the signal-to-noise ratio (SNR) performance of the projection sequences. For the denoising method of the dynamic image sequence, commonly used methods are recursive filtering in the temporal domain [12,13], and some other motion compensation methods such as the temporal and spatial linear minimum mean-square-error (LMMSE) filter proposed by Samy and Sezanl [14,15], the Wiener filter proposed by Kokaram [16], and the mean filter proposed by Martinez [17]. The motion compensation methods are effective in reducing the motion blur and decreasing the random noise to some extent. However, for a high-level-noise dynamic image sequence, we found that their denoising ability was not ideal.

The basic principles of the denoising algorithms can be summarized as less blur in the texture region and much smoother in the flat region [18–20]. According to the principles, a non-local means (NL-means) denoising method was developed and more frequently adopted in computer visualization. This method assumes that the image noise obeys a Gaussian distribution and motion is not needed to estimate for denoising. However, for images with low contrast and high-level noise, the original NL-means method can easily lead to over-blurred artifacts in the flat region of the image [21–23].

For the fast continuous rotation scanning mode, high stability of the rotating motion and accurate synchronization of the communication responses between the control terminals and the host PC are needed to ensure the accuracy of the projection location. The rotation step angle needed in the reconstruction algorithm is determined by the motor's rotation speed and the detector's frame frequency. For example, in processing tomographic imaging (4D-CT), a projection sequence of a specimen is captured over a period of time during which the total rotation angle is far beyond $2\pi$. Before performing 3D-reconstruction, the projection sequence must be divided into several segments so that the rotation angle span of each segment equals $2\pi$ exactly. Here, we define each complete segment as a periodic projection sequence. In theory, through the rotation speed and frame frequency, each complete segment can be pinpointed exactly, and the corresponding projections among $2\pi$ can be extracted for volume reconstruction.

However, because of the deceleration of the motor in the ending stage, fluctuation of the rotation speed, as well as the response lag of the control terminal to the host PC, it can be difficult to guarantee the location accuracy of each periodic projection sequence. Furthermore, because all of the periodic projection sequences are arranged in a serial line, if one sequence is located inaccurately, the following sequences can be affected. This kind of deviation may cause visible artifacts in CT images. Kumar et al. [24] proposed an available discrimination method by calculating the variance between the initial projection (at 0°) and its following projections among a certain neighborhood to realize the location of $2\pi$ angle projection. The position where the variance reaches its minimum value indicates the position of the $2\pi$ angle. For the scanning mode under our consideration, the specimen rotates continuously with a fast speed and the detector collects images with a high frame frequency. The motor makes a full turn within 15 s, and the imaging frame frequency is 50 to 100 frames per second. In this case, we found that Kuma's method could lead to unstable results because