Micro-CT for Minute Objects with Central Ray Determined Using the Projection Data of the Objects

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Abstract. Central ray is the projection of the centre-of-rotation of a computed tomography (CT) system. It is required for all kind of CT image reconstruction algorithms. The current common practice is to determine it by scanning a wire phantom. This is a manual work and very time-consuming. Besides, when a minute object is scanned with large magnification, it usually encounters large errors in the determination of the central ray due to the mechanical movements required. When the source-to-object distance becomes further smaller, it might be even impossible to insert the wire phantom. This paper describes the basic idea of directly using the projection data of an object to be inspected for the determination of the central ray. With this method, the left and right boundary points of the whole-round projection of the object are identified from the sinogram of one slice and the system projection geometry is used to calculate the central ray. This approach significantly simplifies the micro-CT scanning process and saves much operation time as well. The inspections of a small electronic die and a small electric wire-bundle successfully demonstrate the effectiveness of this method.

1. Introduction

Today, X-ray micro-computed tomography (CT) has become an essential tool in the semiconductor and electronics industries to detect and locate small hidden defects as high-density packaging techniques and multilayered structures are increasingly integrated into manufacturing practices.

All computed tomography reconstruction algorithms used today require the knowledge of the central ray, which is the projection of the center-of-rotation (COR) on the detector. The current common practice is to determine it by scanning a wire phantom made of dense metal material before scanning the object to be inspected. However, the use of such a wire phantom not only dramatically leads to a time-consuming calibration process, but also will generate meaningful errors in the central ray determination when the object is placed very close to the source, which would degrade the quality of the reconstructed image by introducing so called 'tuning fork' artifacts [1, 2]. Furthermore, when the source-to-object is smaller than the radius of the wire phantom, this calibration is even not possible at all.

The ideal solution to the mentioned problems would be to determine the central ray directly using the projection data of the object to be scanned; however, no such algorithms so far are available with a fan beam micro-CT system until recently the author suggested a novel method[3]. This paper reports how to use this method to determine the central ray of minute objects which are placed very close to the source and demonstrate the reconstructed CT images of the object slices based on the central ray obtained. For comparison purpose, the central ray determined by the traditional method with a wire phantom is also presented, which shows a big variation in the repeatability study of the calibration.

2. Micro-CT System and the Novel Method for Central Ray Determination

2.1 A typical micro-CT system

Fig. 1 illustrates a schematic representation of a typical modern micro-CT system that is used widely for industry applications. It consists of a fixed X-ray source, a fixed flat panel X-ray detector and a manipulator/rotator for holding, moving and rotating the part to be inspected. The manipulator is usually a high precision positioning stage that can move at least in the *x, y* and/or *z* directions and the rotator can rotate around an axis that is aligned as good as possible to one dimension of the detector array. An X-ray fan beam is generated from the X-ray source, passing through the part and projecting on the detector. The magnification of the system is adjustable through changing the distance between the object and the source. For a CT inspection, the object under investigation is either rotated a whole round or an angle of 180 plus the fan-bean-angle and projection images are taken at equal angular increments.

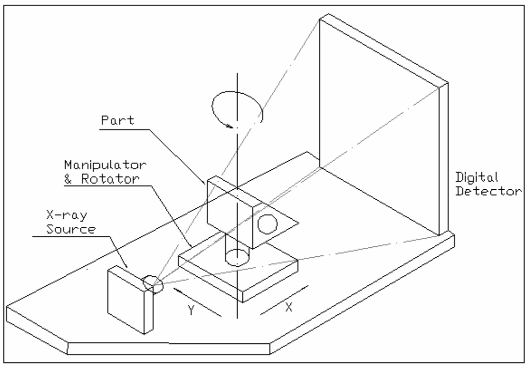


Fig. 1 Schematic diagram of a typical micro-CT system

2.2 Central ray determination principle

Fig.2 describes the geometrical relationship between several important parameters of the micro-CT system and the basic idea of the central ray determination method proposed by the author in [3]. In this illustration, an object with several balls of different radius is used for the CT inspection. With a scan of a whole circle, only the ball with the longest radius generates the widest projection on the detector. In other words, the left and right boundaries of the sinogram of a selected slice actually come from the longest-radius ball on that slice of object. Therefore, once the position of the center-of-rotation is given, the angle of $\angle MSN$ is determined only by the radius of this longest-radius ball. By finding the corresponding scan angles of the left and right boundaries of the projection, the angle of $\angle MSN$ can be calculated, which in turn leads to the determination of the central ray which must bisect the angle of MSN.

Although theoretically this is true, however, because the two boundary points are actually the two tangential points on the circle trajectory of the longest-radius ball, it is not easy to accurately identify corresponding scanning angles. As a result, the central ray is hard to be accurately determined too. A better way is to make use of central channel which is the projection of the x-ray ray perpendicular to the detector plane. With this consideration, the central ray can be determined by

$$\overline{OC} = \left(\frac{\overline{SC}}{p}\right) * tg\left\{\left[tg^{-1}\left(\frac{\overline{LC} * p}{\overline{SC}}\right) - tg^{-1}\left(\frac{\overline{CR} * p}{\overline{SC}}\right)\right] / 2\right\} \tag{1}$$

where $\overline{SC}$ is the source-to-detector distance (unit: µm); p is the pixel size of the detector; $\overline{OC}$, $\overline{LC}$, $\overline{RC}$ are vector distances from the central ray point O, the left end of projection L and the right end of projection R to the central channel point C respectively (unit: pixel). The detector is defined starting from the left side and increase in the right direction.

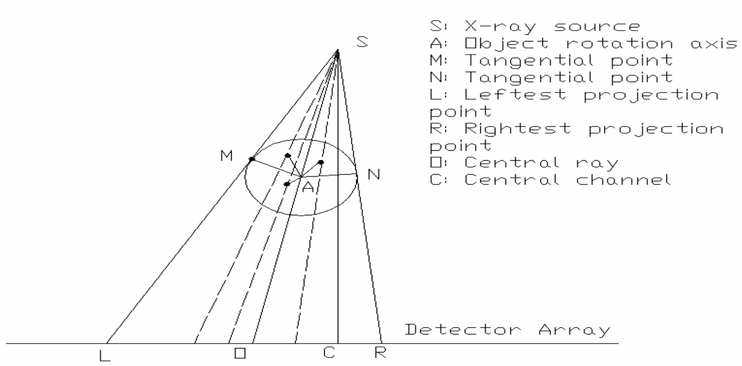


Fig. 2 The geometrical relationship of the CT system

The central channel C is a fixed parameter and only need to be recalibrated when some movement conducted to the camera in possible system maintenance or camera repair.

If both $\overline{LC}$ and $\overline{RC}$ are small so that $\tan x \approx x$ is true, the central ray can be simply determined as the center of $\overline{LR}$, that is,

$$\overline{LO} = \frac{1}{2}\left|\overline{LC} + \overline{CR}\right| \tag{2}$$

3. CT Scanning of Minute Objects and Data Processing Results

In this study, we will inspect a die which is used in hearing-aid electronics and a small electrical wire-bundle. The former has a rectangle shape and its size is about 3.8mm by 5mm. The later has a diameter of about 1mm, consisting of 16 metal wires that are encapsulated in plastic tube. A Feinfocus X-ray inspection system is used for this study. It uses a direct digital detector (DDD) with a 179mm by 234mm active area(Model: Paxscan 2520). The manipulator is controlled and images are captured through G-code programming. Data processing is performed through Matlab programming.

3.1 Central ray determination with traditional method

For comparison purpose, we first investigate the repeatability of the central ray determination by the traditional method. The wire phantom is scanned at a manipulator height of 24.466mm, which corresponds to an SOD of 10mm. Because the wire phantom we used has a diameter of 10mm, the selected SOD is still large enough for scanning it. However, in this situation, one has to move the manipulator away from the source so that he can change the object with the wire phantom and vice versa to avoid any possible risk of crashing with the source. The repeatability study is carried out in this way: the wire phantom is scanned at the same position for five times. In between two scans, the manipulator is moved away from the source, the wire phantom is dismounted from the rotator and then mounted back. This process is similar to that happens in a real CT scan process. The central rays determined in this way are summarized in table 1. One can note that the difference between the minimum and the maximum can be as large as 5.69 pixels. This kind of large error should be mainly brought by the mechanical movements.

Table 1. Central ray calibration repeatability study with a wire phantom at small SOD

Time	**1**	**2**	**3**	**4**	**5**	**Max-Min**
Central ray	675.620	678.934	681.310	679.963	679.372	5.69

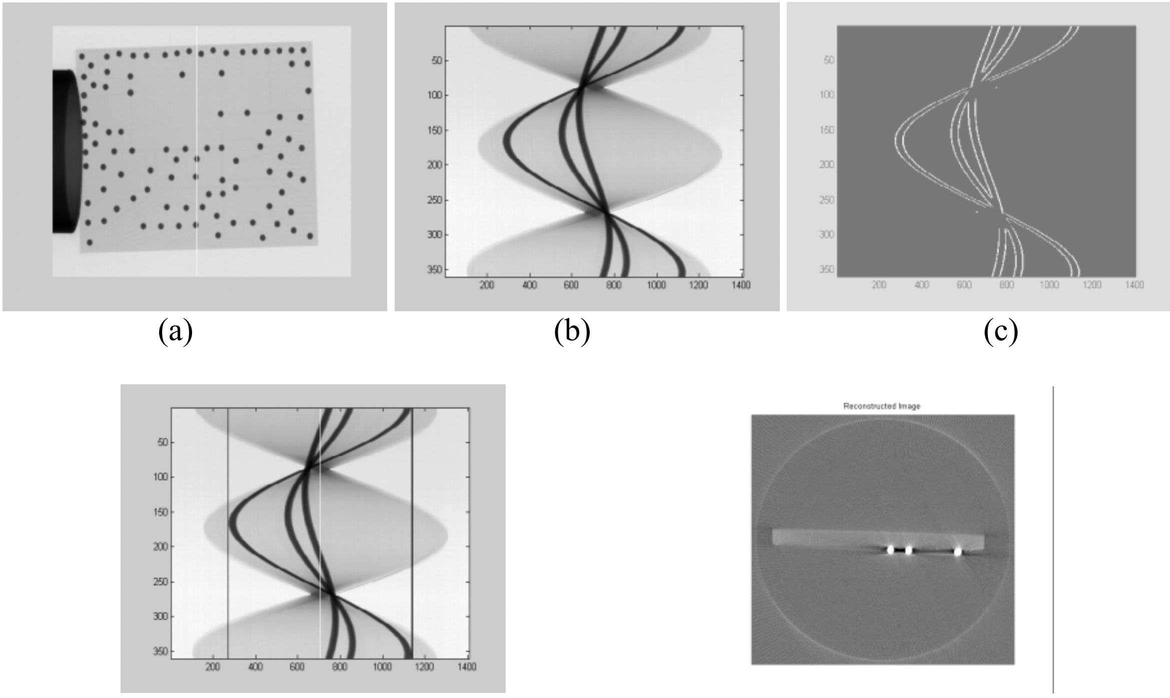
Manipulator position: x=171.257mm; y=158.651mm;z=24466; SOD=10mm ; SID=680.000mm ;
Tube voltage = 120keV; Tube current = 10uA

3.2 CT scanning of a hearing-aid die and a small electrical wire bundle

The hearing-aid is scanned first at 115kV tube voltage and 13μA tube current. The source power in this situation is about 1.4W and just higher than the 1W requirement for a nano-focus spot size. The object is scanned at a manipulator height of 30.03mm ($SOD \approx 15.58$ mm) and the magnification is about 44. The manipulator y position is 157.662mm for this scan. One of the projection images is shown as Fig. 3(a). A projection sinogram of one object slice is shown as Fig. 3(b) (the slice position is 912 in Fig. 3(a)), with which an edge detection algorithm is applied row by row and a threshold is set to identify the edge points on each row. Fig. 3(c) shows the result of edge detection from which two arrays are formed, one holding all the left edge points and another all the right points. Then the left and right boundary points of the whole sinogram are determined as the minimum in the left edge-point array and the maximum in the right edge-point array respectively. Afterwards, with a known central channel position and a known pixel size, the central ray is determined using Eq. 1 to be 705.55(cell number on the detector), as illustrated as white line in Fig. 3(d), although shown in this figure are the two boundary points identified. The reconstructed image of this slice is shown as Fig. 3(e). There is no post processing for this CT image.

Similarly the electric wire is scanned at the same position but with a 108kV tube voltage and 7mA tube current. The source is still working in the nano-focus mode. The object is scanned at 24.466mm manipulator height ($SOD \approx 10$ mm) which gives a magnification of about 68. The manipulator y coordinate is 158.123mm. The projection data of the wire bundle is processed using the same program as for the hearing-aid die. One of its 2d projections, the sinogram of one object slice with boundary points identified, and the reconstructed CT image of this slice are shown as Fig. 4(a), Fig. 4(b) and Fig. 4(c) respectively. The central ray determined with this slice is 713.07.

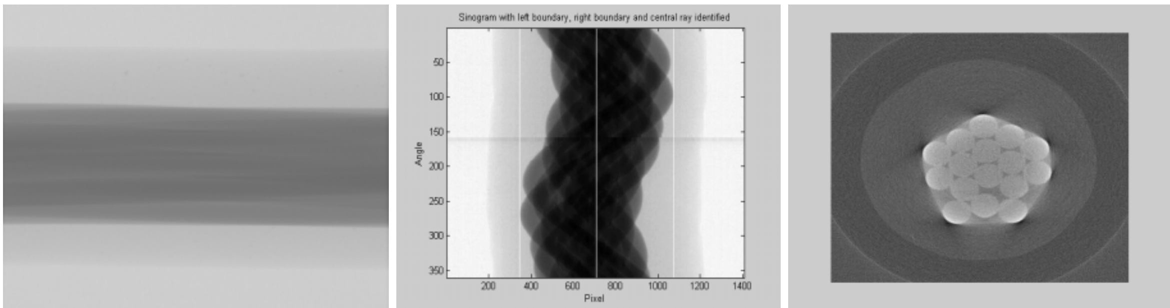
It should be pointed out the central ray determined for the repeatability study with the wire phantom and the two objects are different because they are scanned at slightly different manipulator positions (on both y and z directions). This small adjustment is usually necessary because of the different shape, size and the status of mounting the object. However, it will not affect any conclusion that has been drawn so far.



(a) (b) (c)

(d) (e)

Fig. 3 CT scan of a hearing-aid die: (a) A 2D projection; (b) the sinogram of one slice with the two boundaries (black lines) and central ray (white line) identified; (c) the reconstructed image of the slice in (b)



(a) (b) (c)

Fig. 4 CT scan of a segment of electric wire bundle: (a) A 2D projection; (b) the sinogram of one slice with the two boundaries (black lines) and central ray (white line) identified; (c) the reconstructed image of the slice in (b)

3.3 Accuracy of the new central ray-determination method

The quality of CT images reconstructed in this way has been proofed well enough in general CT scan applications, compared with those obtained with commercially available CT system. However, special situations might be encountered that poor edge contrast leads to the failure of the correct edge detection with a generally selected edge detector size or threshold. As a result, different edge detector size or threshold should be considered. Besides, the boundary points do not necessarily come from the physical boundary of the object to be scanned, instead, they can be projections of some internal structures which presents a much clearer edge.

In the author's opinion, the accuracy of the new method might be affected by the uniformity and stability of both the source and detector, spot size of the source and the power of the edge detection processing. The Feinfocus system we used has a nano-scale spot size with power below 1W and it becomes 1-2 microns when working in range 1W to 3W. The unsharpness produced by it may have the order of 1 pixel size with a magnification of about 50. However, the impact of the unsharpness must be roughly symmetric to the left and right boundary and would not bring in significant error to the central ray determination. By contrast, the edge detection plays an important role in the accuracy issue. Some general edge detection techniques may be good enough to give an accuracy of 0.5 pixels. For some of the applications, localized curve fitting techniques may produce better accuracy in the determination of the central ray.

Conclusion

When minute objects are scanned very close to the source in order to obtain a large magnification, traditional central ray determination method by scanning a wire phantom might produce large errors, or is even impossible. This work describes the basic idea of how to use the projection data of the object to be inspected to directly determine the central ray. This method not only simplifies the calibration process, but also eliminates the possible errors brought by the mechanical movements as required in traditional method. The CT scans of a small electronic die and a small electric wire-bundle successfully demonstrate the effectiveness of this method.

References

[1] L. A. Shepp, S. K. Hilal, and R. A. Schulz, "The tuning fork artifact in computerized tomography," *Computer Graphics Image Processiing*, Vol. **10**, 246-255 (1979).

[2] S. G. Axevedo, D. J. Schneberk, J. P. Fitch and H. E. Martz, "Calculation of the rotational centers in computed tomography sinograms," *IEEE Transaction on Nuclear Science*, Vol. **37**(4) 1525-1540 (1990).

[3] T. Liu, 'Computed tomography system and method', *Patent*, International application no: PCT/SG2005/000354

[4] T. Liu and A.A. Malcolm, " Comparison between four methods fro central ray determination with wire phantom in micro-CT system", *Optical Engineering*, accepted, (2005)