Digital 3d x-ray microtomographic scanners for electronic equipment testing

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Abstract. The article studies the operating procedures of an X-ray microtomographic scanner and the module of reconstruction and analysis 3D-image of a test sample in particular. An algorithm for 3D-image reconstruction based on image shadow projections and mathematical methods of the processing are described. Chapter 1 describes the basic principles of X-ray tomography and general procedures of the device developed. Chapters 2 and 3 are devoted to the problem of resources saving by the system during the X-ray tomography procedure, which is achieved by preprocessing of the initial shadow projections. Preprocessing includes background noise removing from the images, which reduces the amount of shadow projections in general and increases the efficiency of the group shadow projections compression. In conclusion, the main applications of X-ray tomography are presented.

1. Introduction
Modern science allows analyzing the internal microstructure of objects by means of various methods. The method of X-ray microtomography is considered to be one of the best ways of nondestructive imaging. X-ray microtomography allows visualization of the internal structure of nontransparent objects in three dimensions (3D) with high spatial resolution. There is a need to examine the internal structure of nontransparent objects, especially biological ones, in the visible range of the electromagnetic radiation with micron resolution. The development of X-ray microscopy methods has allowed looking inside nontransparent objects with resolution that exceeds the capabilities of optical microscopy. Today, computer microtomography is a primary method of 3D visualization of the internal microstructure of organic and inorganic objects using X-rays. The method is similar to medical imaging, but it has significantly higher spatial resolution. Scanning visualizes the entire internal 3D structure of the object and completely preserves the sample for other studies [1,2]. Methods of digital X-ray imaging allow carrying out studies of both organic and inorganic objects and materials, identifying statistical features of composition and structure of the samples [3 – 5].

2. Basic principles of x-ray microtomography
The work process is as follows: the X-Ray unit irradiates the object that is placed on the controlled operating area. Penetrating the object, X-rays are received by the detector element unit, which provides element-by-element recognition the full frame image of the internal structure of the object.

Let us consider a kinematic scheme of the intelligent 3D X-ray microtomographic scanner (XRMTS). Figure 1 shows the kinematic diagram of the device. During the survey, the sample rotates by 180 or 360 degrees with a fixed pitch. A shadow (transmission) image of the sample is fixed for each micro-rotation. The system saves all these projections as 16-bit tiff files. After scanning, the data array

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represents a set of normal transmission X-ray images. The number of files in the array depends on the step size and the value of the selected total rotation angle. For example, for a 180 ° rotation angle with 0.9 ° step, the data array will contain 200 images and a small number used to transform images to compensate for the correctness of the X-ray beam.

Completion of the sample shooting is followed by reconstruction of its image. The obtained 16-bit shadow tiff images are used to reconstruct virtual sections of the object. Further, using the reconstruction algorithm, a preliminary array of sections is generated. These data are not yet images; it is a matrix containing the absorption values in the section under reconstruction.

![Figure 1. Kinematic diagram of the device](image)

The size of the matrix is similar to the number of pixels inside the section or the line of the CCD matrix (n is a number of pixels in the line of the shadow image or the CCD matrix). Now we can save the reconstructed section as a floating-point matrix containing attenuation values after reconstruction [2].

Completion of formation of the preliminary array of sections is followed by creation of a 3D image of the sample.

3. X-ray 3d microtomograph resolution

Let the resolving power of the tomographic scanner be the quantitative measure of accuracy of tomographic images reconstruction. We will define it as the minimum distance between two opaque objects, which allows us to distinguish these objects on the reconstructed tomogram.

Let us consider the main factors, which determine the resolving power of reconstructed tomographic images. Obviously, the limiting value of the resolving power (the minimum distance resolved by the given tomographic scanner) is determined by the width of the diffraction half-shadow area. Figure 2 shows the dependence between the modulus of the Fresnel integral (which determines the ratio of the level of the diffraction field beyond the obstacle to the level of the field in free space) and excess of the observation point above the obstacle edge by $u$. The value $u$ is measured in the dimensions of the first Fresnel zone. The maximum value of $|F(u)|$ equal to 1.85 is reached when $u \approx 1.2$ (this value is marked by a dashed line in Figure 1). The total diffraction curve obtained when illuminating two objects, will contain two distinguishable maxima if the distance between objects is more than $\Delta_1$. The value $\Delta_1$ is determined by the level of $\frac{1}{\sqrt{2}}$ from the maximum value and is equal to $\Delta_1 = 1.2\sqrt{2}\lambda d$, where $\lambda$ is the
radiation wavelength, \( d \) is the distance between the radiation source and the receiver. When \( d = 0.2 \) m, \( \lambda = 2.3 \cdot 10^{-10} \) m, the value \( \Delta_1 \) is about 13 \( \mu \)m.

Figure 2. The values of the Fresnel integral modulus determine the ratio of the diffraction field amplitude to the level of the field in free space. Dashed lines indicate the width of the area, which determines the minimum separation of distinguishable objects.

Spatial distribution of the diffraction field intensity is recorded at the receiving aperture. A set of registered distributions is the Radon transform of the spatial distribution of the optical density of the object under investigation. This density is restored by the registered projections by means of inversion of the Radon transform. To estimate the accuracy of the reconstruction of the optical density distribution (accuracy of the reconstructed tomogram), we use simplified representations about the inversion procedure of the Radon transform. [6,7]

Traditionally, when calculating the fast Fourier transform (FFT) according to the Cooley-Tuckey algorithm, a technique that significantly reduces the level of quantization noise in the spectral region is used. This method consists in dividing the computation results in each step by 2. Using this technique, estimation of the quantization noise at the output of the calculator can be obtained in the form

\[
\sigma^2 = \frac{2}{3} \cdot 2^{-2b} \quad \text{when} \quad b = 16, \quad \sigma = 1.2459 \cdot 10^{-5}.
\]

The value

\[
\sigma_A = \frac{\sqrt{\sigma^2_x + \sigma^2}}{S(X_0)} \approx \frac{1.25 \cdot 10^{-5}}{0.4341} = 28.8 \cdot 10^{-6} \text{ m}
\]

characterizes deterioration of the system resolution because of the thermal noise of the receiving system and the quantization noise of the analog-to-digital converter (ADC) [8].

The overall resolution of the entire system \( \delta \) can be estimated by summing the values \( \Delta_1, \Delta_2 \) and \( \sigma_A \):

\[
\delta = 1.2 \sqrt{\lambda d} + \frac{2 \cdot \Delta y}{\cos(\Delta \rho)} + \sigma_A.
\]

4. Experimental results

The study was conducted using the following algorithm: 1) turn on the intelligent X-Ray microtomographic scanner and the computer; 2) run the software of the X-Ray microtomographic scanner; 3) run (warm up) the X-ray tube; 4) install the sample on the table of the intelligent X-Ray microtomographic scanner; 5) scan the sample. After the sample is scanned, the images are collected in a single reconstruction. With high resolution of 1-13 micron, 3D-reconstruction of the objects allows investigating previously inaccessible areas at any angle specified by the operator without destroying and damaging the sample. The method of X-ray micro tomography of materials or living objects and tissues does not require sample cross sections. Scanning of the objects under study allows obtaining complete
information on the internal spatial microstructure of the sample with micron and submicron spatial resolution, preserving the structure of the sample or the lives of animals tested. 

The examples of the reconstructed materials (triple diode, crystal triode, light emitting diode) by means of the intelligent X-Ray microtomographic scanner are shown in Figures 3–5.

**Figure 3.** 3D reconstruction of a triple diode

**Figure 4.** 3D reconstruction of a crystal triode
Figure 5. 3D reconstruction of a light emitting diode (LED)

Specifications of the intelligent X-Ray microtomographic scanner include:
- Distinguishability: 1–13 microns.
- X-ray source: smoothly adjustable from 20 to 160 kV, anode current: 0 – 250 mA, 10 W, the focal spot size: <5 mm (≅ 4 Watts), air-cooled.
- X-ray sensor: 2048×2048; 12-bit digital X-ray camera with 27.6×27.6 mm field of view.
- Data Recovery time: 10 (min / cm³).
- Analysis of 3D images of 60 (min / cm³).

5. Conclusion
The developed intelligent X-Ray microtomographic scanner for testing of materials of different origin has the following distinctive advantages:
1) high precision positioning system that is able to position objects under study with the accuracy of ± 1 micron;
2) complete automation of the X-ray micro tomography process and reconstruction of a 3D-model of the object;
3) built-in algorithms and classification analysis of the internal structure and defects of objects;
4) built-in algorithms for pre-processing of initial lossless compression data in order to save computing resources of the system;
5) high operating speed of both hardware and software components because of the use of tunable control algorithms providing significant accuracy of the X-ray microtomographic scanner [9].

Competitive advantages of the developed device include portability, compactness, ability to test different materials (organic, nonorganic, and constructive) and elements of electronic equipment, compatibility with other types of equipment, and competitive price [10].
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