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, 4].

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.

The analog signal from the detector is digitized by an analog-digital converter and is led to the electronic computing machine. A digital signal from the second analog-digital converter, modifying the signal of the control unit of power spectrum of X-ray radiation, enters the second input of the electronic computing machine. The control unit of power spectrum of X-ray radiation measures the spectral components of the signal received from the detector unit [5, 6].
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 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.

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. 3d-reconstruction analysis
Using the 3D image reconstruction unit (3D IRU), a three-dimensional image of the internal structure of the object is reconstructed by its shadow projections (Figure 2). Next, a defectoscopy unit detects discontinuities (defects, cracks, inclusion of garbage, etc.). Then, a pseudo color image-shaping unit (PCISU) presents a pseudo-color image on the monitor screen using information from the 3D IRU. Via the Internet connection unit, the results of the device operation are transferred to the Internet system from the defect detection unit and PCISU.
Algorithmic support of the defect detection unit is based on the gradient, correlation and fractal methods as well as wavelet and Fourier analysis described below.

An array of density values at each point of the sample is initial data for the gradient analysis method. Based on these values, the density function of the material $\rho(x, y, z)$ is determined followed by construction of a gradient field of the sample. Defects will be detected by the field nonuniformity, that is, by the presence of density gradients:

$$\nabla \rho(x, y, z) = \left(\frac{\partial \rho}{\partial x}, \frac{\partial \rho}{\partial y}, \frac{\partial \rho}{\partial z}\right).$$

It is possible to determine the size and nature of the defects by the volume arrangement of these gradients.

Advantages of this method include:
- possibility to determine the defect type;
- possibility to determine the defect location;
- possibility to determine geometric and physical characteristics of the defect.

The gradient of the image $f(x, y)$ is defined at the point $(x, y)$ as a two-dimensional vector:

$$G[f(x, y)] = \begin{bmatrix} G_x \\ G_y \end{bmatrix} = \begin{bmatrix} \frac{df}{dx} \\ \frac{df}{dy} \end{bmatrix}.$$  

From the vector analysis, it is known that the vector $G$ indicates the direction of the maximum change in the function $f$ at the point $(x, y)$. However, when determining defects, the modulus of this vector is of interest; it is usually called as a gradient and is denoted as $G[f(x, y)]$, where

$$G[f(x, y)] = [G_x^2 + G_y^2]^{1/2} = \left[\left(\frac{df}{dx}\right)^2 + \left(\frac{df}{dy}\right)^2\right]^{1/2}.$$  

In practice, as a rule, the gradient is approximated by absolute values

$$\cdot G[f(x, y)] \approx |G_x| + |G_y|.$$  

This approximation greatly simplifies implementation of the method.

The gradient calculation is based on finding the first derivatives $\frac{df}{dx}$ and $\frac{df}{dy}$. There are several ways to do it for digital imaging. One of the approaches is to use the difference between neighboring points

$$G_x = \frac{df}{dx} = f(x, y) - f(x-1, y),$$

$$G_y = \frac{df}{dy} = f(x, y) - f(x, y-1).$$

Figure 2. Block diagram of the 3D image reconstruction unit.
Another method, which is more complicated, involves points in the neighborhood of 3x3 size centered at the point \((x, y)\):

\[
G_x = \frac{\partial f}{\partial x} = f(x, y) - f(x, y - 1).
\]

\[
G_y = \frac{\partial f}{\partial y} = [f(x + 1, y - 1) + 2f(x + 1, y) + f(x + 1, y + 1)] - [f(x - 1, y - 1) + 2f(x - 1, y) + f(x - 1, y + 1)] = (g + 2h + i) - (a + 2b + c),
\]

\[
G_x = \frac{\partial f}{\partial y} = [f(x - 1, y + 1) + 2f(x, y + 1) + f(x + 1, y + 1)] - [f(x - 1, y - 1) + 2f(x, y - 1) + f(x + 1, y - 1)] = (c + 2e + i) - (a + 2d + g),
\]

Where the letters from \(a\) to \(i\) denote neighboring points of the center \((x, y)\). Calculation of the gradient in the 3x3 area is more advantageous than using equations (1) and (2) because of a larger averaging, which makes the gradient less noise-sensitive. In principle, use of wider neighborhoods in finding the gradient is also possible.

Currently, two main directions of the wavelet transform have become widespread. The first direction is continuous wavelet analysis, the main applications of which include localization and classification of the signal singular points, as well as calculation of its various characteristics and frequency-time analysis. The second direction is discrete wavelet analysis, the main application of which is compression of video information, as well as image processing. The result of the wavelet transform with high information content is characterized by a large amount of computation, and, as a rule, by the redundant representation of the results (in comparison with the Fourier transform). This is primarily because of the fact that the wavelet transform allows calculating the relative contribution of frequencies at each point of time (by finding convolution with different-scale versions of the wavelet).

Consequently, it is possible to observe evolution of a spectrum analogous to Fourier, but not for a selected period of time, as in the case of the Fourier transform, but over the entire time interval. Thus, for informative decomposition of the original signal it is sufficient to know its wavelet transform on some rare grid in the time-frequency plane. Analysis of literature data shows that even high-quality and high-contrast images obtained by means of various information and measuring equipment carry a large number of various distortions, noise fields, etc. This interferes with the operation of image processing algorithms and requires additional efforts for suppression and elimination of distortions.

The wavelet spectrum of the images is also exposed to various distortions related to noise properties of signals. It should be noted that the concept of “noise” is connected with the type of image processing and the same effect can be interpreted differently in various image-processing tasks such as tracing, compression, texture processing, etc. In this paper, the concept of “noise” is associated with the factors that prevent proper detection of a useful signal (forming deformation relief on the surface). Let us list the main “disturbing” factors:

- “white noise” (associated with transformation of the light field into an electrical signal);
- distortion of the constant component in the signal (low-frequency noise);
- high-frequency filling (high-frequency noise);
- texture noise, not related to the method of obtaining a two-dimensional signal.

The main (basic) ways of solving the noise-filtering problem include the following operations. The “white noise” can be eliminated by a linear signal filtering (for example, a linear average filter) or a nonlinear “median” filtering. Distortions of the constant component can be eliminated either by spectral methods or by reduction to zero of the constant component in the bounding sliding window.

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 3 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 $\Delta_1 = 1.2\sqrt{\lambda d}$, 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 µm.

![Figure 3](image)

*Figure 3.* 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 [3, 4].

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

$$\sigma^2 = \frac{2}{3} \cdot 2^{-2b}.$$  

When $b = 16$, $\sigma = 1.2459 \cdot 10^{-5}$. 

5
The value \( \sigma_\Delta = \sqrt{\sigma_\Delta^2 + \sigma_\Delta^2} \) \( \approx \frac{1.25 \cdot 10^{-5}}{0.4341} \approx 28.8 \cdot 10^{-6} \) 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).

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

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

In the general form, the operating scheme of the XRMTS algorithm can be written as follows:

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Start → I → E → M → H → D → T → IS → A → Disp → End
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Let us explain the meaning of the operators introduced.

1. The operator **Start** means start of the XRMTS operation: the nodes and units of the XRMTS are prepared for operation (resetting, clearing the memory, etc.), and instruction is given to the synchronizer that determines the sequence of operations.

2. The operator **I** means installation of a sample (the object of investigation) in the working area (the surface of the table). This operation is preceded by preparation of a sample (assurance of the sample size).

3. The operator **E** includes an electromechanic system and a monitoring system for the operation parameters by displaying on the monitor the metrological support unit.

4. Operator **M** includes a metrological provision unit, including a color television control system, as well as the XRMTS security system. Here, fulfillment of the condition \( q \) is required: the object of investigation does not exceed the required dimensions and physical characteristics (for example, hardness, because external vibrations do not affect the measurement), otherwise, control functions pass to one of the operators Start, I, E.

5. Operator **H** includes a high-voltage power supply and a system for monitoring stability of its operation by means of displaying it on the screen of the metrological provision unit.

6. Operator **D** includes a detector that perceives the x-ray signal passing through the object of investigation. The detector converts the X-ray signal into an analog electrical, and then into a digital one. Here, the power supply and cooling units of the detector are turned on.

7. The operator **T** generates test signals for testing all modules (electronic, mechatronic and software), evaluates their state and gives an enabling signal in case of compliance of the XRMTS with the technical requirements.

8. The operator **IS** forms an array of two-dimensional images of the object under investigation when it is moved and rotated in the working area; (i.e. the operator provides image sensing when scanning the object of investigation). Here, fulfillment of the condition \( p \) is required: the power of X-ray radiation is sufficient for conducting measurements, all XRMTS modules function correctly, otherwise, the control functions pass to one of the operators Start, I, E, M, H, D.

9. Operator **A** analyzes a three-dimensional image and performs the following operations:
   a) restores the 3D image of the internal structure of the material;
   b) processes the image (filters, poses);
   c) analyzes discontinuities (defects) of the material;
   d) represents a color three-dimensional image (colors discontinuities).

10. Operator **Disp** displays and transmits the received information.
11. Operator **End** indicates the end of the XRMTS operation.

4. **Conclusions**

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 restructurable control algorithms providing significant accuracy of the X-ray micro tomographic scanner [7].

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 [8, 9].

**Acknowledgement**

The paper is prepared within the framework of the competitiveness improvement programme of National Research Tomsk State University and grant of the Russian Foundation for Basic Research No 16-29-04388.

The authors wish to thank Tatiana B. Rumyantseva from National Research Tomsk State University for English language editing.

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