Multiple robots (robotic centers) and systems. Remote sensing and non-destructive testing

Роботизированные комплексы и системы.
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RESEARCH ARTICLE

Tomographic task solution using a dichotomous discretization scheme in polar coordinates and partial system matrices invariant to rotations

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Abstract
Objectives. The purpose of this work was to create an effective iterative algorithm for the tomographic reconstruction of objects with large volumes of initial data. Unlike the convolutional projection algorithm, widely used in commercial industrial and medical tomographic devices, algebraic iterative reconstruction methods use significant amounts of memory and typically involve long reconstruction times. At the same time, iterative methods enable a wider range of diagnostic tasks to be resolved where greater accuracy of reconstruction is required, as well as in cases where a limited amount of data is used for sparse-view angle shooting or shooting with a limited angular range.
Methods. A feature of the algorithm thus created is the use of a polar coordinate system in which the projection system matrices are invariant with respect to the rotation of the object. This enables a signification reduction of the amount of memory required for system matrices storage and the use of graphics processors for reconstruction. Unlike the simple polar coordinate system used earlier, we used a coordinate system with a dichotomous division of the reconstruction field enabling us to ensure invariance to rotations and at the same time a fairly uniform distribution of spatial resolution over the reconstruction field.
Results. A reconstruction algorithm was developed on the basis of the use of partial system matrices corresponding to the dichotomous division of the image field into partial annular reconstruction regions. A 2D and 3D digital phantom was used to show the features of the proposed reconstruction algorithm and its applicability to solving tomographic problems.
Conclusions. The proposed algorithm allows algebraic image reconstruction to be implemented using standard libraries for working with sparse matrices based on desktop computers with graphics processors.

Keywords: nondestructive technics, X-ray computed tomography, iterative algorithm, system matrix

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НАУЧНАЯ СТАТЬЯ

Решение томографической задачи с использованием дихотомической схемы дискретизации в полярных координатах и парциальных системных матриц, инвариантных к вращениям

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Резюме
Цели. Цель работы состояла в создании эффективного итерационного алгоритма для томографической реконструкции объектов с большими объемами исходных данных. В отличие от сверточного алгоритма проецирования, широко используемого в коммерческих промышленных и медицинских томографах, алгебраические итерационные методы реконструкции используют значительные объемы памяти и характеризуются большими временными затратами на реконструкцию. В то же время итерационные методы позволяют решать более широкий круг диагностических задач, где требуется большая точность реконструкции, а также в случаях использования ограниченного объема данных при малоракурсной съемке или съемке с ограниченным угловым диапазоном.
Методы. Особенностью созданного алгоритма является использование полярной системы координат, в которой проекционные системные матрицы инвариантны по отношению к вращению объекта. Это дает возможность значительно сократить объемы памяти для хранения проекционных матриц и использовать для реконструкции графические процессоры. В отличие от простой полярной системы координат, используемой ранее, нами была использована система координат с дихотомическим делением поля реконструкции, что позволяет обеспечить инвариантность к вращениям и в тоже время достаточно равномерное распределение пространственного разрешения по полю реконструкции.
Результаты. Был разработан алгоритм реконструкции, основанный на использовании парциальных системных матриц, соответствующих дихотомическому делению поля изображения на парциальные кольцевые области реконструкции. С использованием цифровых фантомов Шеппа – Логана и Де Фриза были исследованы особенности работы предложенного алгоритма реконструкции и показана его применимость для решения томографических задач.

Выводы. Предложенный алгоритм дает возможность реализовать алгебраическую реконструкцию изображения с использованием стандартных библиотек для работы с разреженными матрицами на базе настольных компьютеров с графическими процессорами.

Ключевые слова: неразрушающий контроль, компьютерная томография, итерационный алгоритм, системная матрица

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INTRODUCTION

There are two main approaches for resolving tomographic tasks of object reconstruction from projection data. The first approach is based on the application of analytical reconstruction formulation in a fan beam for 2D or a cone beam for 3D geometry [1–3]. This assumes the acquisition of a complete data set in the scanning angular range larger than 180° with a small angular scanning step. The second approach involves the use of a matrix formulation of the tomographic task using regularizing functionals and iterative reconstruction algorithms.

The advantage of the second approach consists in the possibility of using an incomplete dataset for tomosynthesis tasks with limited angular range [4, 5], or for resolving tomography tasks with a limited number of projections [6–11]. Another advantage of algebraic reconstruction is the ability to reduce the influence of metallic artifacts. This is achieved by allowing incorrect tomographic data to be excluded from the reconstruction without the need to find a suitable interpolation to replace them [12].

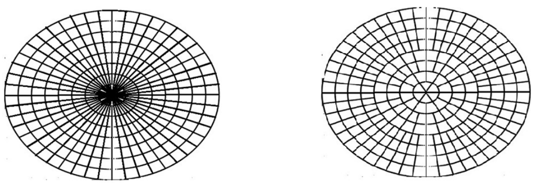
At present, graphic processors are widely used for tomographic reconstruction, accelerating calculations by dozens of times. In the case of 3D tomography, the use of a system matrix in a Cartesian coordinate system, containing all information about the survey geometry, is difficult. This is due to the huge data volume, which makes its storage in the graphics processor memory impossible. Therefore, in iterative reconstruction, multiple ray tracing is applied online using special means of programming parallel computational threads of the graphics processor, as, for example, in *TIGRE* software package [13].

When using the system matrix, optimized libraries of sparse matrix computations can be used on a graphics processor, greatly simplifying software development. The development of software tools for image processing and artificial intelligence tasks is based on libraries of algebraic procedures for working with matrices and vectors. They are constantly updated to work on various stationary and mobile computing platforms.

A number of industrial 3D tomographs utilize a circular imaging geometry in which the object, located between the X-ray source and the high-resolution matrix detector, rotates on a stage. If we use a polar coordinate system centered on the object's rotation axis, it can easily be seen that by proper selection of the radial line pitch corresponding to the angular rotation pitch, the imaging geometry and its corresponding system matrix become invariant with respect to rotation with discrete pitch. This enables the use of a single system matrix computed for only one angular position, instead of computing anew for tens or hundreds of different angular positions in the case of a Cartesian coordinate system. Thus, the system matrix can be entered into the limited memory of the graphics processor and accelerate calculations.

RESEARCH METHODS

In order to calculate the system matrix in the polar coordinate system, we used the Siddon algorithm [14]. Here the lengths of the segments of its intersection with the coordinate lines are calculated for each ray. A disadvantage of the conventional polar coordinate system is that the azimuthal size of the voxel increases as it moves away from the center of rotation. In order to minimize this undesirable effect, a dichotomous division of the image reconstruction field was used in accordance with Fig. 1.



(a) (b)

Fig. 1. Simple polar (a) and dichotomous (b) schemes for discretization of the reconstruction area

In the dichotomous image discretization scheme, each doubling of the radius of polar lines doubles the number of azimuthal lines. Thus, the object image is constructed from a consecutive series of circular segments with indices $ind = 0, 1, 2, \ldots, N$, the outer radius R_{ind} of which is given by the formula:

$$R_{ind} = 2^{ind} R_0,$$

where R_0 is the radius of the central segment with zero index.

In each ring segment, pixels are indexed by two indices, the polar string index i:

$$i = 1, \ldots, m,$$

$$m = 2^{ind} - 2^{(ind-1)},$$

and azimuthal column index j:

$$j = 1, \ldots, n,$$

$$n = 6 \times 2^{ind}.$$

In accordance with known system matrix formalism, two-dimensional indexing is replaced by a one-dimensional one using the column index J given by the formula:

$$J = (j - 1)m + i.$$

Thus, in this discretization scheme, each image can be represented as a set of concentric ring images, each of which is a matrix vectorizable in the above-mentioned way. As a result, each image can be represented as a vector $\mathbf{X}$ composed of vectors $\mathbf{X}_{ind}$, for each of which there is a different matrix $\mathbf{A}_{ind}$ partial matrix of direct projection of the fan bundle, carried out using the formula:

$$\mathbf{B}_{ind} = \mathbf{A}_{ind}\mathbf{X}_{ind},$$

where $\mathbf{B}_{ind}$ is the partial projection. The resulting tomographic projection $\mathbf{B}$ is the sum of projections from all annular segments:

$$\mathbf{B} = \Sigma\mathbf{B}_{ind}.$$

$$\mathbf{B} = \mathbf{AX},$$

where the resulting projection matrix $\mathbf{A}$ is a horizontal concatenation of the matrices $\mathbf{A}_{ind}$:

$$\mathbf{A} = [\mathbf{A}_1\ \mathbf{A}_2 \ldots \mathbf{A}_N].$$

The vector $\mathbf{X}$, respectively, is the vertical concatenation of the vectors $\mathbf{X}_{ind}$:

$$\mathbf{X} = \begin{matrix} \mathbf{X}_1 \\ \ldots \\ \mathbf{X}_N \end{matrix}.$$

In order to take angular scanning into account, the total system matrix needs to be vertically increased, and, accordingly the partial matrices according to the number of selected angles. In this case, there is no need to create new partial matrices if the radial lines of the corresponding partial annular segment coincide during angular rotation by a discrete angle $\Delta\theta$. If the angle of alternation of the radial lines of the ring segment coincides with the angle $\Delta\theta$ of the scanning step, a single partial matrix is sufficient. For example, a 1° step scan over a 360° interval using Cartesian discretization would require at least 90 different partial matrices for each angular position of the object. Thus, in the case of polar discretization, the memory size required to store a single system matrix would be reduced by almost 2 orders of magnitude. When moving to previous ring segments of smaller radius, the number of partial matrices grows dichotomously. However, it can easily be seen that the number of columns of these matrices corresponding to the number of elements of the ring segment decreases proportionally to the degree of number 4. Based on this, we can conclude that when using dichotomous polar discretization of the object, the memory size required to store the system matrix in comparison with Cartesian discretization decreases in proportion to the number of the aspect views.

RESEARCH RESULTS

The standard Shepp–Logan phantom was chosen for the numerical experiment. Due to the distinct features of the dichotomous division of the image radius, the phantom size in Cartesian pixels was chosen as 512 × 512. In terms of matching their information capacity, the size of the reconstruction area in pixels roughly corresponds to the format of digital panel detectors. Using this phantom and the equal-angle distribution of 780 rays in the fan beam, projection data were generated for $6 \times 2^7 = 768$ projections at Cartesian pixel partitioning of the phantom. Then, partial system matrices for 8 segments were generated and used to iteratively reconstruct the object in the polar coordinate system using the classical Landweber algorithm for gradient descent on a quadratic inviscid functional [15]. The iterative procedure was accelerated using the method of moments.

Figure 2 shows the reconstructed images of the digital phantom for different number of iterations. Reconstruction in the dichotomous system provides an acceptable image quality. However, the reconstructed image shows ring artifacts caused by the fact that during iterations the ring regions have different convergence rates to their limit. Increasing the number of iterations from 50 to 500 made the artifacts almost indistinguishable.

(a) (b)

Fig. 2. Phantom reconstructions: (a) 50 iterations, (b) 500 iterations

In order to verify the possibility of using the dichotomous scheme for 3D tomographic reconstruction with a large volume of data, a numerical experiment was performed using the de Vries digital phantom, used in modeling volumetric reconstruction with a wide conical beam. The modeling was performed in *MATLAB*[1] environment for circular imaging geometry. The parameters are specified in the table below.

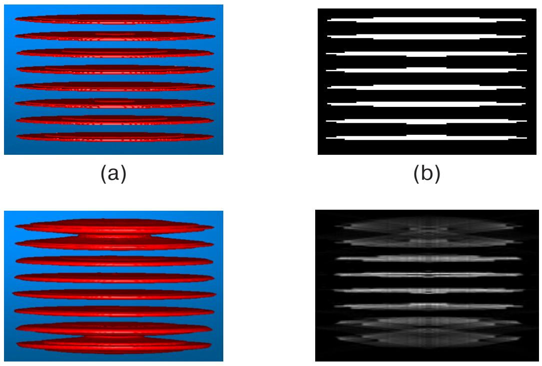
Reconstruction results of the de Vries digital phantom are shown in Fig. 3.

A comparison of the original and reconstructed phantoms shows that reconstruction by the algebraic method, as well as Feldkamp's algorithm, does not fully restore the shape of the outermost disks. This is apparently due to the violation of the Kirillov–Tuy condition, occurring in circular imaging geometry with a wide cone beam [16].

Accelerated gradient descent using Nesterov's method of moments was used for image reconstruction. In total, 40 iterations and 440 s were required for their implementation in *MATLAB* environment when using GeForce RTX 2080 graphics card (NVIDIA, USA). Analysis of the reconstruction program operation showed that the distinct features of the *MATLAB* environment interpreter are associated with large calculation time required to organize the iterative process independently of the user. This can include *MATLAB* system procedures in addition to computational iterative procedures. In our case, the operation of projecting a vector by a partial matrix with the maximum index takes 0.0004 s. At optimal organization of the computational process, one iteration should take no more than 2 s. For 40 iterations, the total reconstruction time should not exceed 2 min which is comparable to the reconstruction time of this

Table. Shooting geometry parameters for digital phantom

Distance from the radiation source to the center of rotation, mm	300
Distance from the center of rotation to the detector, mm	138
Registration field size on the flat panel detector, mm^2	600 × 220
Detector pixels size, mm^2	1 × 1
Reconstruction field size, mm^3 (length × width × height)	256 × 256 × 128
Angular range of rotation, °	0–359
Number of rotation steps	768
Phantom size, mm^3 (length × width × height)	256 × 256 × 128



(c) (d)

Fig. 3. De Vries phantom: (a) volumetric image, (b) cross-section and its reconstruction result (c) volumetric image, (d) cross-section

digital phantom by the conjugate gradient method using the *TIGRE* package.

When implementing the proposed algorithm at a lower level in C++ with CUDA extension, a 32-bit data storage format is acceptable instead of the 64-bit representation allowed in *MATLAB* for sparse matrices. Moreover, top gaming video cards have 24 GB of allocated graphics memory. If we take into account that algebraic reconstruction enables the use of less data volume for reconstruction, we can conclude that the proposed algorithm enables applying computational capabilities of a personal computer for solving a wide range of tomographic tasks. Based on this algorithm, desktop computing systems can feasibly be created for training and modeling the operation of CT scanners in order to optimize their parameters [17, 18].

Thus, the paper proposes a workable discretization scheme combining the advantages of the polar system (invariance to rotations) and the Cartesian system (approximately equal pixel density). The application

[1] https://www.mathworks.com/products/matlab.html. Accessed June 14, 2024.

of the polar coordinate system without dichotomous pixel division used in [19] can result in a different correspondence between the number of pixels of the ring segments and the number of pixels of their corresponding detector segments. While this correspondence will be correct for the outer segments, i.e., the number of corresponding pixels will be approximately the same, the information capacity for the inner regions of the corresponding detector region will be insufficient. This will lead to underdetermination of the system of linear equations, and consequently to the need to use regularization, in order to avoid the appearance of various artifacts typical for tomography with limited data. On the other hand, if the number of corresponding detector pixels for the inner regions is sufficient, the number of data for the outer regions will be excessive. In this case binning must be used for the outer regions of the detector, in order to save memory and speed up reconstruction.

CONCLUSIONS

When using a desktop computer with modern video cards, the use of a dichotomous polar scheme of image division into pixels creates possibilities of iterative algebraic image reconstruction with minimal memory consumption. Applied to a range of tasks of X-ray nondestructive testing, these possibilities will be investigated in numerical simulations on digital phantoms and experimental studies on a desktop microtomograph with a microfocus X-ray source and a large-format digital detector.[2]

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Authors' contributions

A.A. Manushkin—conceptualization and research design, computer simulation, working with graphic material, and writing the text of the manuscript.

N.N. Potrachov—project administration, writing and editing original draft, critical review. Analysis and systematization of the results obtained. Conducting comparative analysis. Generalization of research results. Formulation of conclusions.

A.V. Stepanov—supervision, monitoring research activities.

E.Yu. Usachev—conceptualization, funding acquisition.

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