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A COMPARISON BETWEEN LINEAR BACKPROJECTION (TRANSPOSE) AND LAYERGRAM BACKPROJECTION METHODS FOR IMAGE RECONSTRUCITON IN CHARGED-COUPLE DEVICE (CCD) BASED OPTICAL TOMOGRAPHY

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Abstract. The image reconstruction process for CCD-based optical tomography with four projections is discussed in this paper. The CCD linear image sensor used in the study is a Sony ILX551A which has 2048 pixels with a pixel size of 14-microns. The pixel arrangement used in the system is a combination of octagonal and square pixels to ensure that light passes through the same number of pixel rows on all four projections. Two image reconstruction methods are discussed and compared in the paper – the transpose method and the layergram method. The transpose method involves the multiplication and inversion of matrices while the layergram method is simply the addition of the values of attenuation coefficients. The layergram method was found to produce better images than the transpose method, qualitatively and quantitatively (values of α). However, the transpose method requires a shorter processing time than the layergram method.

Keywords: Optical; tomography; CCD; image reconstruction

Abstrak. Proses pembinaan semula imej untuk tomografi optik berasaskan CCD dengan empat unjuran dibincangkan dalam kertas kerja ini. Deria imej linear CCD yang digunakan dalam projek ini adalah Sony ILX551A yang mempunyai 2048 piksel dengan saiz piksel 14-mikron. Susunan piksel yang digunakan dalam sistem ini adalah gabungan piksel berbentuk oktagon dan segi empat sama untuk memastikan bahawa cahaya merentasi bilangan baris piksel yang sama pada keempat-empat unjuran. Dua kaedah pembinaan semula imej dibincangkan dan dibandingkan dalam kertas kerja ini – kaedah *transpose* dan kaedah *layergram*. Kaedah *transpose* melibatkan pendaraban dan pembalikan matriks manakala kaedah *layergram* adalah penambahan nilai-nilai *attenuation coefficient*. Didapati bahawa kaedah *layergram* menghasilkan imej yang lebih baik daripada kaedah *transpose*, dari segi kualiti dan kuantiti (nilai α). Namun, kaedah *transpose* memerlukan masa pemprosesan yang lebih singkat berbanding kaedah *layergram*.

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Kata kunci: Optik; tomografi; CCD; pembinaan semula imej

1.0 INTRODUCTION

Tomography offers a unique opportunity to unravel the complexities of a structure without the need to invade the object [1]. There are many different forms of tomography. Modern variations of tomography involve gathering projection data from multiple directions and feeding the data into a tomographic reconstruction software algorithm, which is processed by a computer. This is commonly known as computed tomography. Optical tomography is a form of computed tomography that creates a digital volumetric model of an object by reconstructing images made from light transmitted and scattered through the object [2].

Image reconstruction is the process of generating an image from raw data, or a set of unprocessed measurements made by an imaging system. In general, there is a well defined mathematical relationship between the distribution of physical properties in an object and the measurements made by the imaging system. Image reconstruction is simply the process which inverts this mathematical process to generate an image from the set of measurements [3].

In an optical imaging system such as the one used in this study, the light intensity is exponentially attenuated by the object density along the optical path. The natural logarithm of the ratio of the incident intensity to the transmitted intensity is equal to the line integral or ray sum of the distribution of linear attenuation coefficients within the object along the path (Beer-Lambert law of absorption). An image of the object density distribution can be created using a back-projection reconstruction algorithm.

It is important to choose or to develop a suitable reconstruction algorithm for a particular application. Measurement sensors and the requirements for the image vary from application to application [1]. Linear back-projection algorithms have the advantage of low computation cost. However, further research is required to reduce the image reconstruction time and the amount of memory required to process the data.

Tapp *et al.* [4] investigated the potential chemical engineering applications of two electrical process tomography techniques: electrical capacitance tomography (ECT) and electrical impedance tomography (EIT). ECT and EIT produce images based upon variations in permittivity and conductivity, respectively. Methods for reconstructing EIT and ECT images can be broadly divided into three classes: linear single-step and iterative methods, non-linear iterative methods, and heuristic multivariate methods.

Schweiger *et al.* [5] compared some implementation strategies for a Gauss-Newton approach to the inverse solver in optical tomography. In their approach, the non-linear forward model was linearized to produce a Jacobian, and a system of normal equations was developed wherein the Hessian of the forward model is approximated by the Jacobian transposed with itself, plus a regularization term.

Idroas *et al.* [3] discussed the image reconstruction process for a CCD-based optical tomography system with four projections. The image reconstruction method discussed in the paper was the linear back projection method. The inversions of matrices by means of transpose and pseudo inverse were investigated for the linear back projection method. It was found that the transpose matrix gives qualitative information of the image while the pseudo inverse matrix provides quantitative information of the image.

2.0 METHODOLOGY

2.1 The CCD Based Optical Tomography System

The CCD based optical tomography system used in this study consists of four projection systems. Each projection system consists of a ray-box which contains a laser diode, an objective lens and a spherical lens. The CCD linear image sensor is located on the opposite of each ray-box. The CCD linear image sensor used in the system is a Sony ILX551A. It has a resolution of 2048 pixels, with a pixel size of 14 microns by 14 microns. Therefore, in the actual system, the tomographic image is obtained from four projections, with each projection consisting of 2048 measurements [6].

The pixel arrangement used in the system is a combination of octagonal and square pixels to ensure that light passes through the same number of pixel rows on all four projections. The length across each octagonal pixel is 14-microns while the length across each square pixel is 6-microns. Due to the arrangement of the pixels, the octagonal pixel has four projections while the square pixel has only two projections. However, the effect of the pixel shape on the reconstructed image is insignificant in the actual system due to its large number of pixels and small particles of interest.

2.2 Image Reconstruction

Two image reconstruction methods are used to carry out the analyses – i.e. the transpose method and the layergram method.

2.3 The Transpose Method

A forward problem has to be performed first in order to obtain the expected output from known values of the attenuation coefficient for air and the particle. The calculated output from the forward problem will then be used in the back-projection process (inverse problem). The particle is assumed to have a linear attenuation of 10 mm^{-1} and is surrounded by air which has an attenuation coefficient of 0.00142 mm^{-1} [3]. To simplify the analysis, the area of imaging in the pipe is divided into an array of 7 × 7 pixels. The reconstructed image of the particle in air is based on four projections. Each projection has seven optical sensors. Hence, the total number of sensors for four projections is 28. The sensors are labelled M_1 to M_{28}. The linear attenuation of the light is modelled by assuming that each pixel has an attenuation coefficient of α_{ij} where i and j represent the row and column numbers respectively.

Based on the Beer-Lambert Law of absorption, the equations for each projection are as follows:

Projection 1:

$$\alpha_{00}(0.014)+\alpha_{01}(0.006)+\alpha_{02}(0.014)+\alpha_{03}(0.006)+\alpha_{04}(0.014)+\alpha_{05}(0.006)+\alpha_{06}(0.014)=M_1$$

$$\alpha_{10}(0.006)+\alpha_{11}(0.014)+\alpha_{12}(0.006)+\alpha_{13}(0.014)+\alpha_{14}(0.006)+\alpha_{15}(0.006)14+\alpha_{16}(0.006)=M_2$$

and so on until M_7.

Projection 2:

$$\alpha_{00}(0.014)+\alpha_{10}(0.006)+\alpha_{20}(0.014)+\alpha_{30}(0.006)+\alpha_{40}(0.014)+\alpha_{50}(0.006)+\alpha_{60}(0.014)=M_8$$
$$\alpha_{01}(0.006)+\alpha_{11}(0.014)+\alpha_{21}(0.006)+\alpha_{31}(0.014)+\alpha_{41}(0.006)+\alpha_{51}(0.006)14+\alpha_{61}(0.006)=M_9$$

and so on until **M**$_{14}$.

Projection 3:

$$\alpha_{06}(0.014)=M_{15}$$
$$\alpha_{04}(0.014)+\alpha_{15}(0.014)+\alpha_{26}(0.014)=M_{16}$$

and so on until **M**$_{21}$.

Projection 4:

$$\alpha_{66}(0.014)=M_{22}$$
$$\alpha_{64}(0.014)+\alpha_{55}(0.014)+\alpha_{46}(0.014)=M_{23}$$

and so on until **M**$_{28}$.

The expressions shown above can be expressed in matrix form,

$$[S]*[A]=[M] \tag{1}$$

where [*S*] is the sensitivity matrix, [*A*] is the matrix of attenuation coefficients, and [*M*] is the matrix of the measurement values.

To reconstruct the tomographic image, we proceed to solve the inverse problem. Equation (1) is re-arranged to get,

$$[A]=[S]^{-1}*[M] \tag{2}$$

The matrix [*S*] is not square and hence there is no direct inverse. This is the main limitation of the inverse problem as it is virtually impossible to have the number of projections to be equal to the number of pixels involved [3]. Even if [*S*] is square, the inversion is still not possible because the matrix is too sparse. Hence, the transpose method is used to obtain the inverse matrix of S [3].

2.4 The Layergram Method

For the layer gram method, the inverse problem is solved by adding up the measurement values from each projection (M_1 to M_{28}) which correspond to each cell (α_{ij}). For example, the measurement values M_1 (from projection 1), M_8 (from projection 2), M_{18} (from projection 3) and M_{28} (from projection 4) correspond to α_{00}. Similarly, the measurement values M_1 and M_9 correspond to α_{01}.

Therefore,

$$\alpha_{00} = M_1 + M_8 + M_{18} + M_{28}$$

$$\alpha_{01} = M_1 + M_9$$

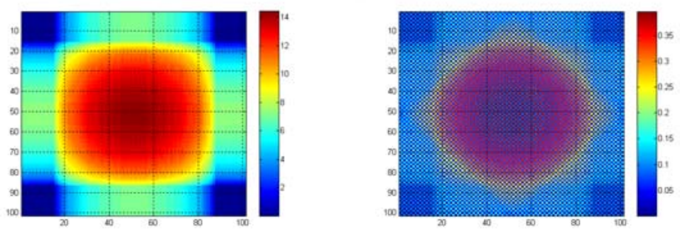
and so on until α_{66}.

4.0 RESULT AND DISCUSSION

Metal rods of various diameters were tested on the CCD-based optical tomography system. The output displays the intensity of shadow detected by the sensor throughout the length of the sensor. The intensity of the shadow formed is measured in volts, with 5 V as the maximum value (total shadow) and 2 V as the minimum value (total light). The values of intensity detected by the sensor are used as the measurement values for the image reconstruction process.

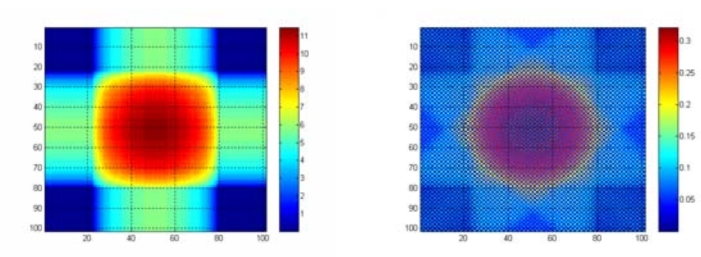
4.1 Tomographic Images

The image reconstruction process was performed on an array of 101 × 101 pixels instead of the full 2048 × 2048 pixels to reduce the required processing time and memory space. Figures 1 to 4 show the images reconstructed from experimental data as well as the images reconstructed by simulation for both the transpose and layer gram method.



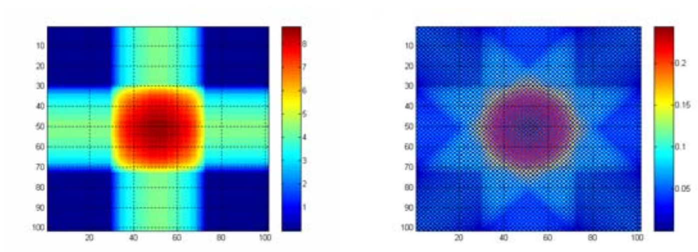
Layer gram Transpose

Figure 1 Simulated images for a 1 mm sample



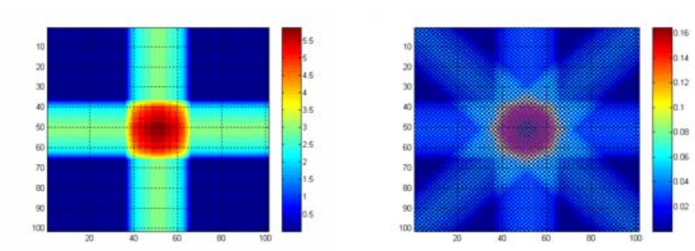
Layer gram Transpose

Figure 2 Simulated images for a 800 µm sample



Layer gram Transpose

Figure 3 Simulated images for a 600 µm sample



Layer gram Transpose

Figure 4 Simulated images for a 400µ sample

As can be seen in the figures above, the images reconstructed from experimental measurement values have a lot of noise, so the images produced are not as clear as the images reconstructed from assumed values of α (simulation). The noise is due to the diffraction of light.

The figures also show that the images reconstructed using the layergram method are brighter and have better contrast than those reconstructed using the transpose method. Besides that, the layergram method also gives better quantitative results, that is to say more accurate values of attenuation coefficient, α. Therefore, it can be said that the layergram method produces better images than the transpose method both qualitatively and quantitatively.

4.2 Processing Time

In addition to comparing the quality of the reconstructed image, the required processing time should also be taken into account. The processing time is simply the time it takes to load the reconstructed image from the moment the computer program is executed. Apart from a good image, it is desirable to have the shortest processing time possible.

Table 1 Image reconstruction processing times

Sample size (μm)	Processing time, t (seconds)	
	Layergram method	Transpose method
1000	8.4	6.5
800	7.5	6.4
600	7.4	6.3
400	7.1	6.3

From the Table 1, it can be seen that the processing time required for the transpose method is shorter than that of the layergram method even though mathematically, the transpose method is more complex than the layergram method. This is probably due to the fact that the computer program for the layer gram method has more commands to execute than the program for the transpose method. However, the difference is small. Hence, it can be concluded that the two methods are comparable in terms of processing time, at least for the number of pixels used for this study i.e. 21 × 21 pixels. For a very large array of pixels, the difference in processing times may be greater.

5.0 CONCLUSION

A unique pixel arrangement with a combination of octagonal and square pixels is required to make the image reconstruction process possible for four projections. A comparison was made between the transpose and layergram methods for image reconstruction. It was found that the layergram method produces better images than the transpose method in terms of brightness, contrast and values of α. However, the transpose method requires a shorter processing time than the layergram method.

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