Tomographic X-ray data of carved cheese

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Abstract

This is the documentation of the tomographic X-ray data of a carved cheese slice. Data are available at \url{www.fips.fi/dataset.php}, and can be freely used for scientific purposes with appropriate references to them, and to this document in \url{http://arxiv.org/}. The data set consists of (1) the X-ray sinogram of a single 2D slice of the cheese slice with three different resolutions and (2) the corresponding measurement matrices modeling the linear operation of the X-ray transform. Each of these sinograms was obtained from a measured 360-projection fan-beam sinogram by down-sampling and taking logarithms. The original (measured) sinogram is also provided in its original form and resolution.

1 Introduction

The main idea behind the project is to create real CT measurement data for testing sparse and limited data tomography algorithms. A sufficiently thin slice of Edam cheese has been carved with CT letters to recover different attenuation coefficients (calcium-containing organic compounds for cheese and air for the carved letters). In particular, the shape of the carved letters makes the target rather challenging for typical sparse and limited angle tomography applications.

A video report of the data collection session is available at \url{https://www.youtube.com/watch?v=omMrkaCxB2E}.

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2 Contents of the data set

The data set contains the following MATLAB\textsuperscript{1} data files:

- `DataFull_512x15.mat`,
- `DataLimited_512x15.mat`,
- `DataFull_256x15.mat`,
- `DataLimited_256x15.mat`,
- `DataFull_128x15.mat`,
- `DataLimited_128x15.mat`,
- FullSizeSinogram.mat and
- GroundTruthReconstruction.mat.

The first two of these files contain CT sinograms and the corresponding measurement matrices with the same resolution but different spanning for the angle of view: the data in files `DataFull_512x15.mat` lead to reconstructions with resolutions $512 \times 512$ with 15 directions spanning the full 360 degree circle; the data in files `DataLimited_512x15.mat` lead to a reconstructions with resolutions $512 \times 512$ with 15 directions spanning a 90 degree angle of view. Similarly, the data in files `DataFull_256x15.mat` and `DataLimited_256x15.mat` (respectively) lead to reconstructions with resolutions $256 \times 256$ ($128 \times 128$, respectively) with 15 directions spanning the full 360 degree circle and a 90 degree angle of view, respectively. The data file named `FullSizeSinogram.mat` includes the original (measured) sinograms of 360 projections, and `GroundTruthReconstruction.mat` contains a high-resolution FBP reconstruction computed from the 360-projection sinogram. Detailed contents of each data can be found below.

`DataFull_512x15.mat` contains the following variables:

1. Sparse matrix $A$ of size 14835 $\times$ 262144; measurement matrix.
2. Matrix $m$ of size 989 $\times$ 15; sinogram (15 projections spanning the full 360 degree circle).
3. Scalar $\|A\|$; norm of the matrix $A$.

`DataLimited_512x15.mat` contains the following variables:

1. Sparse matrix $A$ of size 14835 $\times$ 262144; measurement matrix.
2. Matrix $m$ of size 989 $\times$ 15; sinogram (15 projections spanning the range $1^\circ$–$90^\circ$, i.e., a limited angle of view).

\textsuperscript{1}MATLAB is a registered trademark of The MathWorks, Inc.
3. Scalar \( \|A\| \); norm of the matrix \( A \).

**DataFull_256x15.mat** contains the following variables:
1. Sparse matrix \( A \) of size \( 14835 \times 65536 \); measurement matrix.
2. Matrix \( m \) of size \( 989 \times 15 \); sinogram (15 projections spanning the full 360 degree circle).
3. Scalar \( \|A\| \); norm of the matrix \( A \).

**DataLimited_256x15.mat** contains the following variables:
1. Sparse matrix \( A \) of size \( 14835 \times 65536 \); measurement matrix.
2. Matrix \( m \) of size \( 989 \times 15 \); sinogram (15 projections spanning the range \( 1^\circ – 90^\circ \), i.e., a limited angle of view).
3. Scalar \( \|A\| \); norm of the matrix \( A \).

**DataFull_128x15.mat** contains the following variables:
1. Sparse matrix \( A \) of size \( 14835 \times 16384 \); measurement matrix.
2. Matrix \( m \) of size \( 989 \times 15 \); sinogram (15 projections spanning the full 360 degree circle).
3. Scalar \( \|A\| \); norm of the matrix \( A \).

**DataLimited_128x15.mat** contains the following variables:
1. Sparse matrix \( A \) of size \( 14835 \times 16384 \); measurement matrix.
2. Matrix \( m \) of size \( 989 \times 15 \); sinogram (15 projections spanning the range \( 1^\circ – 90^\circ \), i.e., a limited angle of view).
3. Scalar \( \|A\| \); norm of the matrix \( A \).

**FullSizeSinograms.mat** contains the following variables:
1. Matrix \( \text{sinogram15FullView} \) of size \( 2240 \times 15 \); original (measured) sinogram of 15 projections spanning the full 360 degree circle.
2. Matrix \( \text{sinogram15LimitedView} \) of size \( 2240 \times 15 \); original (measured) sinogram of 15 projections spanning the range \( 1^\circ – 90^\circ \) (limited angle of view).
3. Matrix \( \text{sinogram45FullView} \) of size \( 2240 \times 45 \); original (measured) sinogram of 45 projections spanning the full 360 degree circle.
4. Matrix \( \text{sinogram45LimitedView} \) of size \( 2240 \times 45 \); original (measured) sinogram of 45 projections spanning the range \( 1^\circ – 90^\circ \) (limited angle of view).
5. Matrix \texttt{sinogram180FullView} of size $2240 \times 180$; original (measured) sinogram of 180 projections spanning the full 360 degree circle.

6. Matrix \texttt{sinogram360} of size $2240 \times 360$; original (measured) sinogram of 360 projections.

\texttt{GroundTruthReconstruction.mat} contains the following variables:

1. Matrix \texttt{FBP360} of size $2000 \times 2000$; a high-resolution filtered back-projection reconstruction computed from the larger sinogram of 360 projections of the carved cheese ("ground truth"). See Figure 5.

Also, we provide the user with the MATLAB routine producing the filtered back-projection reconstruction (script file \texttt{FBPgroundtruthRec.m}).

In addition, at \url{www.fips.fi/dataset.php} are available data set with 45 projections (spanning both the full 360 degree circle and the range $1^\circ$–$90^\circ$) and 180 projections (spanning the full 360 degree circle), for the same three resolutions $512 \times 512$, $256 \times 256$ and $128 \times 128$. Similarly to the 15 projections case, the data set names are \texttt{DataFull\_512x45.mat}, \texttt{DataFull\_256x45.mat} and \texttt{DataFull\_128x45.mat} for the 45 projections case spanning the full 360 degree circle, \texttt{DataLimited\_512x45.mat}, \texttt{DataLimited\_256x45.mat} and \texttt{DataLimited\_128x45.mat} for the 45 limited data case (range $1^\circ$–$90^\circ$), and \texttt{DataFull\_512x180.mat}, \texttt{DataFull\_256x180.mat} and \texttt{DataFull\_128x180.mat} for the 180 projections case spanning the full 360 degree circle. All these data sets contains the measurement matrix \( \mathbf{A} \) along with its norm \( \| \mathbf{A} \| \) and the sinogram \( \mathbf{m} \).

\textbf{Remark.} The resolutions of the above datasets are designed specifically so that the total variation regularization parameter choice rule published in [2] can be applied easily. Also, the reason to include the norms of the matrices is the following. Some reconstruction methods require that the norm of the system matrix in equation \( \mathbf{A} \mathbf{x} = \mathbf{m} \) is (at most) one. This can be easily enforced like this in MATLAB:

\[
\mathbf{A} = \mathbf{A} / \| \mathbf{A} \|; \\
\mathbf{m} = \mathbf{m} / \| \mathbf{A} \|;
\]

After these lines of code the equation is equivalent to the original but the norm of the system matrix is one.

Details on the X-ray measurements are described in Section 3 below. The model for the CT problem is

\[
\mathbf{A} \ast \mathbf{x} = \mathbf{m}(:,),
\]

where \( \mathbf{m}(:,) \) denotes the standard vector form of matrix \( \mathbf{m} \) in MATLAB and \( \mathbf{x} \) is the reconstruction in vector form. In other words, the reconstruction task is to find a vector \( \mathbf{x} \) that (approximately) satisfies \( \mathbf{1} \) and possibly also meets some additional regularization requirements. A demonstration of the use of the data is presented in Section 4.
3 X-ray measurements

The data in the sinograms are X-ray tomographic (CT) data of a 2D cross-section of the carved cheese measured with a custom-built μCT device shown in Figure [1]

- The X-ray tube is a model XTF5011 manufactured by Oxford Instruments. This model is no longer sold by Oxford Instruments, although they have newer, similar models available. The tube uses a molybdenum (Z = 42) target.

- The sample manipulator consists of a motorized rotation stage (Thorlabs CR1/M-Z7) mounted onto a motorized horizontal translation stage (Thorlabs LTS300/M), both of which are computer-controlled. The horizontal translation stage allows control of the geometric magnification parameter.

- The flat panel detector is a Hamamatsu Photonics C7942CA-22. The active area of the flat panel detector is 120 mm × 120 mm. It consists of a 2400 × 2400 array of 50 μm pixels. According to the manufacturer the number of active pixels is 2344 × 2240, which yields an active width of 112 mm. However, the image files actually generated by the camera were 2368 × 2240 pixels in size.
Figure 2: *Left:* Experimental setup used for collecting tomographic X-ray data. The detector plane is behind the cheese target with the active area indicated by a white square. The target is attached to a computer-controlled rotator platform. *Right:* Two examples of the resulting 2D projection images. The fan-beam data in the sinograms consist of the (down-sampled) central rows of the 2D projection images.

The measurement setup was designed and assembled in 2015 by Alexander Meaney as a MSc thesis project [1] and recently upgraded (1-3/2017). The setup is illustrated in Figure 1 and the measurement geometry is shown in Figure 3.

A set of 360 cone-beam projections with resolution $2368 \times 2240$ and angular step of one (1) degree was measured. The exposure time was 1000 ms (i.e., one second). The X-ray tube acceleration voltage was 40 kV and tube current 1 mA. See Figure 2 for two examples of the resulting projection images.

From the 2D projection images the middle rows corresponding to the central horizontal cross-section of the carved cheese were taken to form a fan-beam sinogram of resolution $2240 \times 15$ (variables \texttt{sinogram15FullView} and \texttt{sinogram15LimitedView} in file \texttt{FullSizeSinograms.mat}). These sinograms were further down-sampled by binning and taken logarithms of to obtain the sinograms $m$ in all the files specified in Section 2.

The organization of the pixels in the sinograms and the reconstructions is illustrated in Figure 4.

In addition, a larger set of 360 projections of the same carved cheese using the same imaging setup and measurement geometry, but with a finer angular step of one (1) degrees, was measured (variable \texttt{sinogram360} in file \texttt{FullSizeSinograms.mat}). The high-resolution ground truth reconstruction (variable \texttt{FBP360} in file \texttt{GroundTruthReconstruction.mat}) was computed from this data using filtered back-projection algorithm, see Figure 5.
Figure 3: Geometry of the measurement setup. Here FOD and FDD denote the focus-to-object distance and the focus-to-detector distance, respectively; the black dot COR is the center-of-rotation. The width of the detector (i.e., the red thick line) is denoted by W. The yellow dot is the X-ray source. To increase clarity, the $x$-axis and $y$-axis in this image are not in scale.
Figure 4: The organization of the pixels in the sinograms $\mathbf{m} = [m_1, m_2, \ldots, m_{15K}]^T$ and the reconstructions $\mathbf{x} = [x_1, x_2, \ldots, x_{N^2}]^T$, with $N = 128$, $N = 256$ or $N = 512$. The picture shows the organization for the first projection. After that, in the full angular view case, the target takes a 24 degree steps counter-clockwise (or, equivalently, the source and detector take a 24 degree steps clockwise) and the following columns of $\mathbf{m}$ are determined in a similar way; in the limited angular view case, the target takes a 6 degree steps counter-clockwise (or, equivalently, the source and detector take a 6 degree steps clockwise).
Figure 5: The high-resolution filtered back-projection reconstruction \textit{FBP360} of the carved cheese computed from 360 projections.
4 Example of using the data

The following MATLAB code demonstrates how to use the data. The code is also provided as the separate MATLAB script file example.m and it assumes the data files (or in this case at least the files DataFull_512x15.mat and DataLimited_512x15.mat) are included in the same directory with the script file. The resulting reconstructed images are reported in Figure 6.

% Load the measurement matrix and the sinogram for the sparse angle case
load DataFull_512x15
N1 = sqrt(size(A,2));
m1 = m;

% Compute a Tikhonov regularized reconstruction using
% conjugate gradient algorithm pcg.m
alpha = 10; % regularization parameter
fun = @(x) A.'*(A*x)+alpha*x;
b = A.'*m(:);
x1 = pcg(fun,b);

% Load the measurement matrix and the sinogram for the limited angle case
load DataLimited_512x15
N2 = sqrt(size(A,2));
m2 = m;

% Compute a Tikhonov regularized reconstruction using
% conjugate gradient algorithm pcg.m
alpha = 10; % regularization parameter
fun = @(x) A.'*(A*x)+alpha*x;
b = A.'*m(:);
x2 = pcg(fun,b);

% Take a look at the sinograms and the reconstructions
figure
subplot(2,2,1)
imagesc(m1)
colormap gray
axis square
axis off
title(’Sinogram, sparse angles’)
subplot(2,2,3)
imagesc(m2)
colormap gray
axis square
axis off
title('Sinogram, limited angles')
subplot(2,2,2)
imagesc(reshape(x1,N1,N1))
colormap gray
axis square
axis off
title({'Sparse angles'; 'Tikhonov reconstruction,'})
subplot(2,2,4)
imagesc(reshape(x2,N2,N2))
colormap gray
axis square
axis off
title({'Limited angles'; 'Tikhonov reconstruction,'})

References

[1] Meaney, A: Design and Construction of an X-ray Computed Tomography Imaging System. MSc Thesis. University of Helsinki, Department of Physics, 2015. [http://hdl.handle.net/10138/157237](http://hdl.handle.net/10138/157237)

[2] Niinimäki K, Lassas M, Hämäläinen K, Kallonen A, Kolehmainen V, Niemi E and Siltanen S, Multi-resolution parameter choice method for total variation regularized tomography. SIAM Journal on Imaging Sciences 9(3) 2016, pp. 938–974.
Figure 6: First row: sinogram and corresponding Tikhonov regularized reconstruction with 15 projections spanning the full 360 degree circle. Second row: sinogram and corresponding Tikhonov regularized reconstruction with 15 projections spanning the range $1^\circ$– $90^\circ$. 