1 Publications

2015

X. Yang, R. Hofmann, R. Dapp, Th. van de Kamp, T. dos Santos Rolo, X. Xiao, J. Moosmann, J. Kashef, and R. Stotzka. TV-based conjugate gradient method and discrete L-curve for few-view CT reconstruction of X-ray in vivo data. Optics Express **23**, 5368 (2015).

2016

R. Hofmann, A. Schober, J. Moosmann, J. Kashef, M. Hertel, S. Hahn, V. Weinhardt, D. Hänschke, L. Helfen, I. A. Sánchez Salazar, J.-P. Guigay, X. Xiao, T. Baumbach. Gauging low-dose X-ray phase-contrast imaging at a single and large propagation distance. To be published at Optics Express (2016).

S. Hahn, R. Hofmann, J. Moosmann, O. Öktem, L. Helfen, J.-P. Guigay, Th. van de Kamp, and T. Baumbach. Contrast transfer in Fresnel diffraction. With referees at Physical Review A (2016).

2 Software packages

Software packages contributed to:

Operator Disrectisation Library (ODL)

3 Conferences/Workshops

None.

4 Status of development activities

4.1 Characterise application

Action 34: Document the specific characteristics of the inverse problem associated with application A1.

Deadline: 2015-03-10

Deliverables: Report outlining characteristics of the inverse problem in application A1.

Status: Completed.

The acquisition geometry relevant for application A1 is cone-beam with helical (spiral) acquisition curves and flying focal spot (FFS) technique.

Protocol used: head computerized tomography (CT)

Dose: low/normal-dose CT scan: 30 mGy, high-dose scan: 121 mGy. According to clinician Lars-Olof the difference between grey matter (GM) and white matter (WM) could hardly be seen in the low-dose scan while in the high-dose scan the contrast was much clearer.

Protocol parameters

Exposure time: 20 s to 30 s
Scanning length: 150 mm to 210 mm
Nominal single collimation width: 0.6 mm
Total collimation width: 12 mm
Pitch factor (ratio of pitch and collimation width): 0.5 mm to 1 mm
X-ray Modulation Type (FFS): Z_EC
Pulsing: off
KVP: 120 kV
Maximum X-ray Tube Current: 400 mA to 620 mA
Exposure Time per Rotation: 1 s
Mean CTDIvol: 130 mGy
DLP: 1800 mGycm to 2800 mGycm
?tot (beräknad): 9000 to 12 500mAs
?eff (beräknad): 600 to 900mAs

FFS

The protocol for head CT typically involves FFS i. e. a periodic movement of the source in plane (xy-FFS), along the longitudinal direction (z-FFS), or both (xyz-FFS). Thereby, instead of one data set two, three, or four times the number of projections of a non-FFS scan are acquired. This is to improve sampling and to allow for a higher spatial resolution at the same pitch factor or keeping the resolution constant at a higher pitch factor. Additionally, z-FFS reduces helical acquisition artefacts. Typically, FFS reconstruction algorithms employ a rebinning of the projection data to accounts for the divergent source and the source movement followed by a parallel-beam reconstruction. All Scale Tomographic Reconstruction Antwerp (ASTRA)'s projector for cone-beam geometry allows for arbitrary orientations of the detector and arbitrary positioning of the detector reference point and the source. Once the integration weights for a curved detector are implemented, reconstructions can be performed without rebinning.

The xy-FFS is automatically triggered by the acquisition protocol. This usually happens when the pitch factor is ≤ 1 which is the case for the head CT protocol. The z-FFS can be triggered manually which is usually the case for the head CT protocol according to the acquisition protocols obtained from Daniel Thor. Since data processing and reconstruction is completely hidden within the CT scanner, the FFS positions are not accessible by Daniel Thor. However, real xyz-FFS data from an abdomen phantom is provided and available (with restrictions) by Mayo clinic including FFS position values.

To support FFS data acquisition in ODL requires a dedicated geometry class to be implemented. Reconstructions of FFS data should then work using ASTRA given the parameters of source and detector positions.

Simulation of simplistic data

Simulations using GEANT4 Application for Emission Tomography (GATE) to generate a full data sets are not feasible for a realistic phantom, not even for a simplistic phantom since GATE does not scale with phantom complexity. GATE is thus disregarded to create full phantom data set. Instead the Monte Carlo simulator of Jonas is used to generate a full data set from a realistic phantom. This data set can then be validated by comparing a small region of interest of a few projections with a GATE simulation of that region.

A simplistic phantom is created by David and Mamo which incorporates magnetic resonance imaging (MRI) and CT data provided by Carlos Aguilar Palomeque. Relevant features of the simplistic phantom such as GM, WM, and cerebrospinal fluid (CSF) are accurate according to the clinicians Eric and Lars-Olof. David and Mamo are to be provided with new MRI data of a much better quality from the clinicians in order to refine the phantom. In spring 2015 new CT data will be taken at the clinic with potential access to the raw data assuming an agreement with Siemens. According to CT physicist

Daniel Thor reading of the raw data is non-trivial and help by Siemens is preferable. Data will be available for healthy patients and patients with weak and strong atrophy of GM.

Storage data format

The standardised projection data format (SPDF) is an extended, vendor-neutral Digital Imaging and Communications in Medicine (DICOM) format developed at the Mayo clinic which supports axial and helical modes with cylindrical, spherical, and flat detectors, and flying focal spot acquisition [Flo+05]. Each projection data is stored in a DICOM image containing the image and a header.

SPDF assumes a third generation CT gantry geometry i. e. detector and source rotate simultaneously along a circular orbit in the axial plane. SPDF cannot be used for dedicated CT scanners such as interventional C-arm. SPDF allows head-to-head comparison of different reconstruction algorithms.

In addition to SPDF a public library is going to be instantiated by the Mayo clinic in order to provide projection and image data from clinically acquired patient scans for head, chest, and abdomen CT and two common CT systems.

First SPDF data sets from a American College of Radiology (ACR) CT accreditation phantom are acquired from a from Mayo clinic. Once we can handle the data format of the ACR phantom we move on to patient data.

In order to read the additional DICOM tags which contain the relevant information to reconstruct the raw data, a DICOM dictionary is provided for Matlab. To read those DICOM tags using Pydicom I wrote script to create a corresponding dictionary for Pydicom.

CT scanners at Karolinska Institutet (KI)

The CT-scanners at KI are practically a black box regarding data acquisition parameters (except of those listed below) and reconstruction details. KI medical physicist Daniel Thor does not have access to these parameters. Scanners available at KI are (for the sake of completeness positron emission tomography (PET) and single-photon emission computed tomography (SPECT) scanners are also listed):

- Siemens SOMATOM Flash
  contains two X-ray tubes A and B. Parameters for tube A are identical to Siemens SOMATOM Definition AS.
- Siemens SOMATOM Definition AS
  uses: Adaptive Dose Shield or SAFIRE, FAST (Fully Assisting Scanner Technolo-

gies) CARE (Combined Applications to Reduce Exposure) technology, X-ray tube STRATON [Sch+04]

- Siemens Emotion
- Siemens Biograph mCT (PET)
- Siemens Symbia (SPECT)

Pixel size: The pixel size depends on the reconstructed field of view (FOV) which will vary from scan to scan since the operator adjusts this manually depending on patient and anatomy (e. g. FOV is about 20 cm for a head and sometimes up to 50 cm for an abdomen). The matrix is 512×512 and therefore the pixel size is typically between 160/512=0.3 mm and 500/512=0.98 mm. The attenuation correction is usually performed with maximum FOV of 50 cm and 78 cm on the Emotion and Biograph, respectively.

Energy spectrum: the spectrum of the STRATON tube which is used in the Biograph is confidential, but a spectrum simulated e. g. with PCXMC based on kVp and filtration and HVL can be validated by Daniel Thor.

Data preprocessing: from service mode D. Thor concludes that there are a couple of standard raw-data corrections: DefChan, InvLog, AirCal, SliceNorm, WedgeCorr, ChanCorr, BeamHard, WaterScaling. In addition to this the reconstruction kernels have proprietary corrections depending on anatomical region selected e. g. cupping corrections.

Siemens SOMATOM Definition AS / Siemens SOMATOM Flash A:

Time for head scan: 1 s/rotation
Time for body scan: 1 s / rotation
Number of projection: 4608 at 1 s, 2304 at 0.5 s, 1152 at 0.25 s
Detector elements: $47104 = 736 \times 64$
Pitch factor (ratio of pitch and collimation width): 0.55
Detector: UFC ultrafast ceramic, material Gadolinium oxysulfide (Gd_20_2S)
Detector width: $\sim$ 80 cm
FFS: Parameters not available.

Vendor reconstruction algorithm:
Sinogram Affirmed Iterative Reconstruction (SAFIRE); raw-data based semi-iterative reconstruction based on filtered backprojection (FBP) aiming at dose reduction (54 % to 60 %) or improved image quality (contrast, sharpness, noise); Siemens standard weighted FBP; Iterative Reconstruction in Image Space (IRIS)

Definition AS (PET/CT):

Detector size (guess by D. Thor): 0.6*1.2 mm
Detector elements: 47104
Detector rows: 64

Detector row width: 0.6 mm
Source to detector distance: 1085.6 mm
Source to isocenter distance: 595 mm

Filtration:
Tube housing: equivalent to 6.8 mm Al at 145 kV
Additional: 0.3 mm Ti plus 1 mm C (equivalent to 1.6 mm Al at 145 kV)
Bowtie: 0.5 mm Al
HVL: 80 kV typical 5.8 mm to 6.0 mm; 100 kV typical 7.1 mm to 7.2 mm; 120 kV typical 8.1 mm to 8.3 mm; 140 kV typical 9.1 mm to 9.2 mm

Number of projection: 4608 at 360° and 1 s rotation time. But typically scans are performed in helical mode at 0.5 s and a scanner with a fixed sampling rate. Guess by D. Thor: a maximum of 180+θ which means that in practice the number of projection would be $4608/(2/(180+\theta)) \sim 1250$

Emotion (SPECT/CT)

The Emotion has an adaptive array detector: thinner elements in centre rows 16 mm × 0.6 mm and outside of that 4 mm × 1.2 mm on each side, a total of 24 rows. It can only be run in 16-slice mode. $16 \times 0.6 = 9.6$ mm detector or $16 \times 1.2 = 19.2$ mm with the central rows binned 2×2.

Detector size guessed by D. Thor: 0.6 mm × 1.2 mm or 1.2 mm × 1.2 mm depending on the two available
Detector elements: $17664 = (16 + 4 + 4) \times 64 \times 11 = (16 + 4 + 4) \times 16 \times 46$
Detector rows: 24 (adaptive)
Source to detector distance: 940 mm
Source to isocenter distance: 535 mm

Filtration:
Tube housing: equivalent filter of 5.5 mm Al at 140 kV
Bowtie: 0.5 mm Al
HVL: 80 kV typical 5.3 mm; 110 kV typical 6.9 mm; 130 kV typical 7.9 mm;

Number of projection: 1250 at 360° and 1 s rotation time. Body scans are performed in helical mode at 0.6 s

4.2 Forward model software

Action 37: Download, install, and test ASTRA and NiftyRec. Asses to what extent these software suites can be used as forward software in application A1, in particular asses which forward models and data acquisition geometries are supported (see action 34)

Deadline: 2015-03-15

Deliverables: Documentation estimating development efforts needed for using these software suites as forward model application. Assess which forward models and data acquisition geometries are supported.

Status: Completed. Software suites considered are ASTRA, NiftyRec, Reconstruction Toolkit (RTK) and Tomographic Reconstruction in Python (TomoPy).

TomoPy

TomoPy is developed in Chicago for synchrotron beamlines at the Advanced Photon Source (APS) and only supports parallel-beam geometries. It is thus disregarded.

NiftyRec

NiftyRec is now part of occiput. Problems with functions for transmission tomography: back-projector returned an empty reconstruction. This problem is probably fixed (not tested) as of version 2.3.1 because a similar problem was fixed for the SPECT functions. Since NiftyRecs back-projector matches well the adjoint of the forward projector, it is maybe worth reconsidering it. However, the installation procedure is very messy and the developer support is poor. Moreover, issues regarding the matching of forward and back-projector are going to be fixed in ASTRA.

RTK

RTK is based on Insight Segmentation and Registration Toolkit (ITK). It provides forward and back-projectors for cone beam geometries. At Elekta RTK is used for reconstructions using the Feldkamp, Davis, and Kress (FDK) algorithm. Compilation of ITK succeeded, but compilation of RTK failed on my local machine. Therefore RTK wasn't considered anymore from my part. However, since ASTRA's implementation of the FDK algorithm only supports very simple geometries, an ODL issue (#228) is created to support RTK.

ASTRA

ASTRA is the forward model software of choice for the application A1 due to the support of relevant geometries, CUDA accelerated computations, and the good developer support. Geometries supported by ASTRA are

- parallel 2D
- parallel 3D
- fan-beam

- cone-beam with circular acquisition
- cone-beam with helical acquisition

Central Processing Unit (CPU) supported geometries:

- parallel beam (2D) with weights
  - line: the weight of a ray/pixel pair is given by the length of the intersection of the pixel and the ray, considered as a zero-thickness line.
  - strip: the weight of a ray/pixel pair is given by the area of the intersection of the pixel and the ray, considered as a strip with the same width as a detector pixel.
  - linear: a ray is traced through successive columns or rows (depending on which are most orthogonal to the ray). The contribution of this column/row to this ray is then given by linearly interpolating between the two nearest volume pixels of the intersection of the ray and the column/row. This is also known as the Joseph kernel, or a slice-interpolated kernel.
- fan beam (2D) with weights
  - line: the weight of a ray/pixel pair is given by the length of the intersection of the pixel and the ray, considered as a zero-thickness line.
  - strip: the weight of a ray/pixel pair is given by the area of the intersection of the pixel and the ray. The ray is considered as a 2D cone from the source to the full width of the detector pixel. The projector can only be used with the fan-flat geometry. Remark: This mathematical model does not properly take into account the fan beam magnification effect.

Graphics Processing Unit (GPU) supported geometries:

- parallel beam (2D)
- fan beam (2D)
- parallel beam (3D)
- cone beam (3D) with circular acquisition
- cone beam (3D) with helical acquisition

Forward and back-projectors are successfully tested for all geometries.

4.2.1 Visualisation software

Visualisation software suitable for general purposes: arrayShow tool (Matlab), ImageVis3D, MeVisLab, medInria, GIMIAS, FiJi, icy, **vtk!** (**vtk!**) base volume renderers like Para-

View. To analyse neuroanatomical structures for application A1, specialised visualisation software of potential interest is FreeSurfer (FS), FSL, or CIVET.

Action 41: Determine suitable visualisation software for assessing reconstruction quality relevant for application A1.

Deadline: 2015-03-15

Deliverables: Visualisation software for application A1 installed and tested.

Status: Completed. The visualisation software relevant for application A1 is FS. FS is used at KI in clinical applications related to brain CT and Alzheimer's disease (AD).

4.2.2 FS

The software is installed and tested on the provided examples.

Input data format is the output format from the MRI scanner. Typical work flow: load data, segmentation, parcellation, skull striping, intensity normalisation, topology fixer, group analysis, region of interest (ROI), statistics analysis, multi-modal, where the latter ones are optional.[1] The work-flow at KI involves a visual inspection of the quality of the segmentation, parcellation, etc in FS. Frequently, a manual interaction is required for incorrectly rendered regions. Small artefacts involving a few voxels only are not relevant and should not be touched when applying manual corrections. Problematic data occurs when the patient has lesions, trauma, motion, large brain changes caused by strong dementia e. g. a sparse brain mass for elderly people. The latter is very problematic in combination with movement. Trauma e. g. appear 'black' in MRI data and can easily be identified in the reconstructed volume. Patient movement occasionally causes artefact of the skull being included in surfaces. Movement typically appears as ringing artefacts, especially close to the skull. Then the boundary regions appear 'noisy' which is likely to cause that the CSF and the skull are included in the pial surface.

Simple data visualisation of reconstructed volumes is provided within ODL using matploblib.

To do: test FS on volumes reconstructed from data which is simulated using Jonas' Monte Carlo software and the realistic brain phantom created by David and Mamo; convert reconstructed data into MRI data format which can be read by FS

[1] Data processing work-flow using FS:

1. start reconstruction (`recon-all`), optionally with a flag to correct for intensity inhomogeneities
2. check segmentation, parcellation with MRI background
3. edit volume
4. run reconstruction again (`recon-all`)
5. check data again

4.2.3 Reconstruction in a highly simplistic setting

Test software of Section 4.2 by performing a reconstruction from simplistic simulated data using a method already available within the forward-model software in action 34.

Action 45: Reconstruct from simplistic simulated data relevant for application A1 using a method already available within the forward model software selected in action 37.

Deadline: 2015-04-01

Status: Completed in time. Reconstructions using ASTRA's FBP, FDK, or simultaneous iterative reconstruction technique (SIRT) algorithms are successfully tested for all available geometries (including cone beam geometry with helical acquisition). Input data was simulated by ASTRA or GATE.

4.3 Compute forward model and the adjoint of its derivative

Action 51: Develop software components within the platform for variational regularisation (action 50) for computing the forward model for application A1 making use of components from forward model software in action 37. The data acquisition geometries need to support those that arise in simplistic simulated data from action 44.

Deadline: 2015-06-01

Deliverables: Software components within the platform for variational regularisation (action 50) for computing the forward model for application A1 with proper coupling to relevant routines provided by forward model software in action 37. Data acquisition geometries should match those for simplistic simulated data from action 44.

Status: Partly completed. Geometries for simplistic data (parallel beam, cone beam with circular or helical acquisition, and flat detector), ASTRA back-end, and operators (forward and back-projector) are implemented in ODL. The merge of this branch with master is pending.

To do: check scaling for anisotropic pixel size; improve tests; implement weights for the forward projector with a curved detector; create a geometry for FFS data acquisition.

Action 54: Derive analytic expressions for the adjoint of the derivative of the forward model in application A1. Develop software components for within the platform for variational regularisation (action 50) for computing this derivative consistent with routines for the forward model in action 51, typically making use of components from forward model software in action 37. The data acquisition geometries supported need to correspond to those that arise in simplistic simulated data from action 44.

Deadline: 2015-06-15

Deliverables: Software components within the platform for variational regularisation (action 50) for computing the adjoint of the forward model for application A1 with proper coupling to relevant routines provide by forward model software in actions 37 and 51. Data acquisition geometries should match those for simplistic simulated data from action 44.

Status: Partly completed. The adjoint of the derivative of the forward model (the back-projector) is implemented along action 51 for the geometries involving simplistic data (non-curved detectors). The merge of this branch with master is pending.

To do: implement integration weights for the back-projector with a curved detector

Action 58: Develop software components within the framework in action 57 to compute (2.1) and its gradient in the context of application A1. Use software components from actions 51, and 54 for the delegated computation. Ensure resulting routines are computationally feasible for clinically relevant problem sizes and time constraints (action 34).

Deadline: 2015-08-15

Deliverables: Software components within the framework in action 57 for computing (2.1) and its gradient in the context of application A1.

Status: Partly completed. Delay due to action 51 and 54. ASTRA routines use CUDA and thus are computationally feasible. Weighted norms are supported in ODL.

To do: improve data wrapping (currently, ODL's GPU memory and ASTRA's GPU are not shared, thus data has to be copied)

Action 67: Consider energy functionals of 'p-type w.r.t. a dictionary as in (A.9). Derive analytic expressions for its gradient. Using the framework from action 61, implement routines for evaluating (A.9) and its gradient.

Deadline: 2015-09-01

Deliverables: Expression for the gradient of (A.9). Software components within the framework in action 61 for computing (A.9) and its gradient. Here you may assume there are software components for sparse representation and synthesis.

Status: Remains to be completed. Delay due to the delay of action 51, 54, and 58 and due to delay in implementing adequate optimisation methods (primal-dual methods such as the Chambolle-Pock algorithm). Primal-dual methods are frequently used for sparsity promoting optimisation problems. Thus, we could benefit from an interface for primal-dual methods (work in progress).

To do: implement a generic interface for primal-dual formulations of optimisation problems involving proximal operators and convex conjugates of objective functionals; derive analytic expression for the gradient of (A.9)

Action 68: Implement classical Tikhonov regularisation for application A1. The implementation should constitute a component within the platform for variational regularisation (action 50) and it should be applicable to reconstruct from simplistic simulated data generated for application A1 (action 44). Furthermore, it should make use of software components from actions 58 and 62. Make sure to use an optimisation scheme that is computationally feasible bearing in mind the problem size and time constraints associated with application A1 (action 34).

Deadline: 2015-10-01

Deliverables: Implementation of classical Tikhonov regularisation for application A1 within the platform for variational regularisation (action 50) that is computationally feasible for clinically relevant problem sizes and time constraints (action 34).

Status: Partly completed. Tikhonov regularisation can be carried out using the Chambolle-Pock algorithm which is implemented ODL, but merge of this branch with master is pending. Using the algorithm only requires to provide a linear (composite) operator and proximal operators (which are independent of the linear operator except that they share the domain of the range of the operator) as input. Classical Tikhonov regularisation with the Chambolle-Pock algorithm then works by providing proximal operators for an L2-data term and an L2-regularisation and a product space operator combining the forward projector and the spatial gradient operator. Currently, the X-ray transform operator and the Chambolle-Pock algorithm are on different branches.

To do: merge branches containing the Chambolle-Pock algorithm and the ASTRA backend into master.

Action 71: Implement TV regularisation for application A1. The implementation should constitute a component within the platform for variational regularisation (action 50) and it should be applicable to reconstruct from simplistic simulated data generated for application A1 (action 44). Furthermore, it should make use of software components from actions 58 and 63. Make sure to use an optimisation scheme that is computationally feasible bearing in mind the problem size and time constraints associated with application A1 (action 34).

Deadline: 2015-11-01

Deliverables: Implementation of TV regularisation for application A1 within the platform for variational regularisation (action 50) that is computationally feasible for clinically relevant problem sizes and time constraints (action 34).

Status: Partly completed. As in action 68, but simply replace the proximal operator for an L2-regularisation by the one for an L1-regularisation.

To do: as in action 68.

Acronyms

ACR American College of Radiology
AD Alzheimer's disease
APS Advanced Photon Source
ASTRA All Scale Tomographic Reconstruction Antwerp
CPU Central Processing Unit
CSF cerebrospinal fluid
CT computerized tomography
DICOM Digital Imaging and Communications in Medicine
FBP filtered backprojection
FDK Feldkamp, Davis, and Kress
FFS flying focal spot
FOV field of view
FS FreeSurfer
GATE GEANT4 Application for Emission Tomography
GM grey matter
GPU Graphics Processing Unit
ITK Insight Segmentation and Registration Toolkit
KI Karolinska Institutet
MRI magnetic resonance imaging
NiftyRec NiftyRec
ODL Operator Disrectisation Library
PET positron emission tomography
RTK Reconstruction Toolkit
ROI region of interest
SIRT simultaneous iterative reconstruction technique
SPDF standardised projection data format
SPECT single-photon emission computed tomography
TomoPy Tomographic Reconstruction in Python
WM white matter

Bibliography

[Flo+05] T. G. Flohr et al. „Image reconstruction and image quality evaluation for a 64-slice CT scanner with z-flying focal spot". In: *Med Phys* 32.8 (Aug. 2005), pp. 2536–2547.

[Sch+04] P. Schardt et al. „New x-ray tube performance in computed tomography by introducing the rotating envelope tube technology". In: *Med Phys* 31.9 (Sept. 2004), pp. 2699–2706.