STIR
General Overview

Kris Thielemans

version 5.2

SPDX-License-Identifier: Apache-2.0 AND License-ref-PARAPET-license
See STIR/LICENSE.txt for details.

Contents

1 Disclaimer

Many names used below are trademarks owned by various companies. They are fully acknowledged, but not explicitly stated.

This document has been brought somewhat up-to-date for version 5.2, but there is more work to do.

2 Overview

STIR (*Software for Tomographic Image Reconstruction*) is Open Source software (written in C++) consisting of classes, functions and utilities for 3D PET and SPECT image reconstruction, although it is general enough to accommodate other imaging modalities. An overview of STIR 2.x is given in [Thi12], which you ideally refer to in your paper. See the STIR website for more details on how to reference STIR, depending on which functionality you use.

STIR consists of 3 parts.

- A library providing building blocks for image and projection data manipulation and image reconstruction.
- Applications using this library including basic image manipulations, file format conversions and of course image reconstructions.
- Python interface to the library via SWIG.

The library has been designed so that it can be used for many different algorithms and scanner geometries. The library contains classes and functions to run parts of the reconstruction in parallel on distributed memory architectures, although these are not distributed yet. This will enable the software to be run not only on single processors, but also on massively parallel computers, or on clusters of workstations.
STIR is portable on all systems supporting the GNU C++ compiler, CLang++, Intel C++, or MS Visual C++ (or hopefully any C++-11 compliant compiler). The library is fully documented.
The object-oriented features make this library very modular and flexible. This means that it is relatively easy to add new algorithms, filters, projectors or even a different type of image discretisation. It is even possible to select at run-time which version of these components you want to use.
The software is **freely available** for downloading under the Apache 2.0 license. **It is the hope of the collaborators of the STIR project that other researchers in the PET and SPECT will use this library for their own work, extending it and making their work available as well.** Please subscribe to some of our mailing lists if you are interested.
In its current status, the software is mainly a research tool. It is probably not friendly enough to use in a clinical setting. In any case, **STIR should not be used to generate images for diagnostic purposes**, as there is no warranty, and most definitely no FDA approval nor CE marking

3 A bit more detail on the library

The STIR software library uses the object-oriented features of C++:

- self-contained objects hide implementation details from the user (*encapsulation*);

- specialisation of concepts is implemented with hierarchies of classes (*inheritance*);
- conceptually identical operations are implemented using functions with identical names (*polymorphism*).

The building block classes included in this library are as follows:

- information about the data (scanner characteristics, study type, algorithm type, etc.);
- multi-dimensional arrays (any dimension) with various operations, including numeric manipulations;
- reading of various raw data as well as writing in Interfile format;
- classes of projection data (complete data set, segments, sinograms, viewgrams) and images (2D and 3D);
- various filter transfer functions (1D, 2D and 3D);
- forward projection and backprojection operators;
- classes for sparse projection matrices, both for on-the-fly computation and pre-stored;
- trimming and zooming utilities on projection and image data;
- classes for scatter estimation
- classes for normalisation and attenuation correction
- classes for iterative reconstruction algorithms;
- some classes for kinetic modelling and parametric imaging
- stream-based classes for message passing between different processes, built on top of MPI

Examples of hierarchies are given in the following figures:

These figures are extracted from the documentation which is available in HTML, LaTeX and PDF. This documentation is generated automatically from the source files of the library using the `doxygen` tool. This means that it requires minimal effort to keep the documentation up-to-date.

The advantages of such a library are (a) modularity and flexibility of the reconstruction building blocks to implement new reconstruction algorithms, (b) possibility to compare analytic and iterative methods within a common framework, (c) the possibility to use the same software implementation of the building blocks to perform image reconstruction on different scanner geometries and (d) independence of the computer platform on which the software runs.

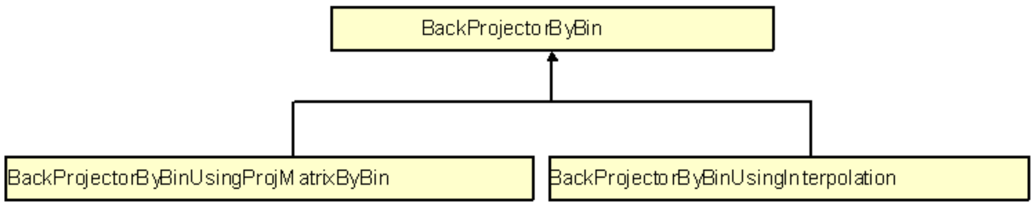

Figure 1: Somewhat outdated hierarchy for back projectors.

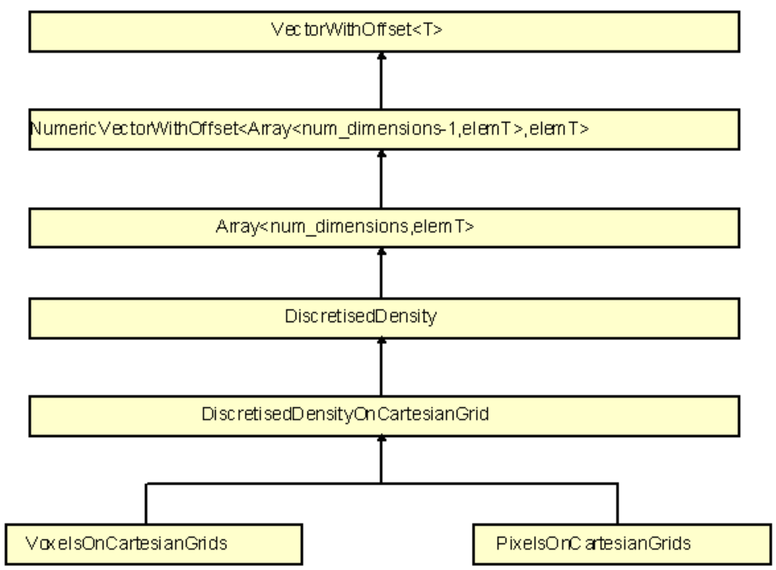

Figure 2: Current image hierarchy

4 Reconstruction algorithms currently distributed

4.1 FBP

Optionally with SSRB first.

4.2 3DRP

The 3DRP [Kin89] algorithm is often considered the 'reference' algorithm for 3D PET. It is a 3D FBP algorithm which uses reprojection to fill in the missing data. However, this is not actively maintained anymore.

4.3 Ordered Subsets Maximum A Posteriori using the One Step Late algorithm

The Expectation Maximization (EM) algorithm [She82] as well as its accelerated variant OSEM (Ordered Set Expectation Maximization) [Hud94] are iterative methods for computing the maximum likelihood estimate of the tracer distribution based on the measured projection data.

One drawback of OSEM is its tendency to develop noise artefacts with increasing iterations. As a remedy, various modifications of the image updating mechanism have been investigated for EM and OSEM to drive the image estimate sequence toward a smoother limit. These include the addition of a smoothing step between iterations (e.g. [Sil90]) and Bayesian methods which incorporate prior information about the smoothness of the object to be reconstructed (e.g. [Gem84], [Heb89]).

Filtering

Different types of filtering strategies are possible (and implemented in STIR). Post-filtering is the most common choice. Inter-iteration filtering filters the image after every (sub)iteration, or at a lower frequency. It probably was poineered in [Sil90] for EMML where it was called Expectation Maximisation Smoothing (EMS). Inter-update filtering is similar. Forward projection of the current image iterate is done first in order to compute the usual ML-EM image of multiplicative weights. These weights are then applied to a filtered version of this image to generate the next iterate, for further details see [Jac99].
See [Sli98] for a comparison between post- and inter-iteration filtering, where it is claimed that both give similar results. [Mus01a],[Mus01b] discusses resolution properties of EMS and shows that it can generate resolution which is object-dependent.

Maximum A Posteriori (Bayesian)

Bayes theorem allows the introduction of a prior distribution into the reconstruction process that describes properties of the unknown image. Maximisation of this *a posteriori* probability over a set of possible images results in a MAP estimate. Priors may be added one by one into the estimation process, assessed individually, and used to guarantee a fast working implementation of preliminary versions of the algorithms [LAL93], [LAN90].

Markov Random Fields (MRF) are used to describe the relationship between adjacent pixels. Gibbs Random Fields (GRF) represent a subset of MRFs which originate from statistical physics, where the problem is to estimate large scale properties of a lattice system from its local properties. Hence, the Bayesian model can utilise a Gibbs prior to describe the spatial correlation of neighbouring regions as was first suggested by Geman et al. in 1984 [GEM84]. The Gibbs prior is controlled by three parameters: one determines the overall weight placed on the prior in the reconstruction process, the two others affect the relative smoothing of noise versus edges in the reconstructed image estimates. Their derivative will act as a penalty term that enforces conditions required by the prior.

The STIR executable OSMAPOSL allows to run a MAP algorithm known as the One Step Late [Gre90] modification of MLEM obtained by multiplying the ML-EM equation by a factor that uses the derivative of an *energy function*. This algorithm works fine for small weights of the prior term, however becomes unstable for larger values.

As prior we currently only distribute the "quadratic penalty", i.e. a Gibbs prior with a qudratic potential function, and a generalisation of the Median Root prior (MRP) [Ale97]. In the MRP case, the assumption is that the desired image is locally monotonic, and that the most probable value of the pixel is close to the local median. MRP has shown very interesting properties in terms of noise reduction, quantitative accuracy, and convergence, see [Bett01]. Our (obvious) generalisation consists in allowing to use other filters than the Median. Other priors can easily be added with some coding.

4.4 OSSPS

An implementation of OSSPS [Ahn03] is included since STIR version 2.1. This algorithm is designed for penalised reconstruction (MAP). When used with a decreasing relaxation constant, it is theoretically convergent [Ahn03]. In practice, it works best when initialised fairly close to the final solution, and when a non-zero background term (e.g. randoms or scatter) is present.

As OSSPS is implemented using the same framework as OSMAPOSL, it is possible to use inter-iteration filtering for OSSPS. Interestingly, [Mus01a],[Mus01b] showed that when used with spatially uniform filtering, this algorithm has nearly object-independent resolution properties, in contrast to EMS.

4.5 Other

We distribute an implementation of FORE [Def97]. It is an efficient rebinning algorithm to reduce the data-size from 3D-PET to 2D-PET.

PARAPET code for Ordered Subsets Conjugate Barrier (OSCB) [Mar99] exists but needs a bit of work to convert to STIR. Please let us know if you want to help.

With respect to dynamic and gated imaging techniques, we have direct estimation of Patlak parameters [Tso08] (using Parametric OSMAPOSL or OS-SPS). We plan to release motion compensated image reconstruction [Thi06] as implemented by Tsoumpas et al [Tso11].

5 Optimisation

Optimisation of the implementation for any particular hardware architecture or intercommunication topology is not attempted in STIR. Therefore the main goals of optimisation and parallelisation were:

- to allow evaluation of the reconstruction algorithms to be carried out within a reasonable time frame; indeed, the parallel versions of the reconstruction algorithms have been extensively used during algorithm evaluation;

- to improve clinical usability of the results of the project; this has been achieved by providing parallel implementations of the algorithms that allow clinicians to run the selected variety of reconstruction algorithms even for very large PET-scanners on MIMD-parallel systems without any knowledge of parallel computing.

6 Software testing strategy

As the STIR software library is quite extensive, it was essential to test its components separately. Due to its modular design, it was possible to have a fairly comprehensive test strategy.

Nearly all basic building blocks have their own test class, checking a lot of test cases. Running of these tests is fully automated.

The projectors have in a first stage been tested interactively. For the forward projector this consisted in forward projecting various images and comparing with the known result. Results were also compared with an independent implementation of a ray-tracing forward projection. For the interpolating backprojector the test which revealed most problems was to backproject uniform data, as this should give (locally) uniform images. The resulting image was also calculated analytically and compared with the building blocks result. Finally, different groups of symmetry were used, cross-checking different parts of the code. Once these tests confirmed properly working projectors, our main strategy consisted in checking results of new versions with the established results.

Aside from these checks, all algorithms can run in a debugging mode where assertions check consistency and validity.

Finally, the web-site also provide the `recon_test_pack`. The distributed script contains consistency checks on the reconstruction (forward simulation followed by reconstruction with various algorithms) and a number of data-sets and expected end-results.

7 Currently supported systems

We regularly run STIR on Lniux, MacOS and Windows. Check our GitHub Actions and Appveyor for details.

Warning: We currently have a problem in the incremental backprojection routines due to different rounding of floating point calculations. You will find out if this problem still exists when you run the recon_text_pack available on the STIR web-site. Please let us know. This currently only affects the FBP routines. See the User's Guide for how to use another backprojector.

7.0.1 Parallel versions of algorithms

- a parallel version of `OSMAPOSL` and `OSSPS` using MPI
- OpenMP versions of many functions
- CUDA versions for NiftyPET and parallelproj

7.1 PET scanners

See `buildblock/Scanners.cxx`.

Other cylindrical PET scanners can easily be added. This can be done without modifying the code (see the Wiki).

7.2 File formats

- An extension of the Interfile standard (see the "Other info" section of the STIR website.)
- ITK can be used to read many image file formats
- Siemens "interfile-like" data
- GE RDF9 (if you have the HDF5 libraries)
- The commercial AnalyzeAVW library from the BIR, Mayo University, can be used to read images via a conversion utility. This will be dropped in version 6.0.
- GE Advance VOLPET sinogram format, but for reading only. This will be dropped in version 6.0.
- ECAT 7 matrix format for reading only might work but is no longer supported. However, this file format needs the ECAT Matrix library (developed previously by M. Sibomana and C. Michel at Louvain la Neuve, Belgium). This library is no longer maintained however.

See the User's Guide for more detail on the supported file formats.
In addition, a separate set of classes is avalailable to read list-mode data. Only a few scanners are currently supported (such as the ECAT HR+ and HR++, GE RDF9, Siemens mMR and SAFIR), although it should not be too difficult to add your own (if you know the list-mode file format!).

8 References

[Ale97] Alenius S and Ruotsalainen U **(1997)** Bayesian image reconstruction for emission tomography based on median root prior. *European Journal of Nuclear Medicine* , Vol. 24 No. 3: 258-265.
[Ahn03]S. Ahn, J. A. Fessler. **2003** Globally convergent image reconstruction for emission tomography using relaxed ordered subsets algorithms. *IEEE Trans. Med. Imag.*, 22(5):613-626.
[Bar97] Barrett H, White T and Parra L C **(1997)** List mode likelihood. *J. Opt. Soc. Am.*, A 14: 2914-2923.
[Ben99a] Ben-Tal A, Margalit T and Nemirovski A **(1999)** The ordered subsets mirror descent optimization method with application to tomography. *Research report #2/99, March 1999, MINERVA Optimization Center, Faculty of Industrial Engineering and Management, Technion – Israel Institute of Technology.*
[Ben99b] Ben-Tal A and Nemirovski A **(1999)** The conjugate barrier method for non-smooth, convex optimization. R*esearch report #5/99, October 1999, MINERVA Optimization Center, Faculty of Industrial Engineering and Management, Technion – Israel Institute of Technology.*
[Bett01] V. Bettinardi, E. Pagani, M. C. Gilardi, S. Alenius, K. Thielemans, M. Teras and F. Fazio **(2001)**, Implementation and evaluation of a 3D one-step late reconstruction algorithm for 3D positron emission tomography brain studies using median root prior, *Eur. J. Nucl. Med, in press.*
[Dau86] Daube-Witherspoon M E and Muehllener G **(1986)** An iterative space reconstruction algorithm suitable for volume ECT. *IEEE Trans. Med. Imaging*, vol. MI-5: 61-66.
[Def97] Defrise M, Kinahan P E, Townsend D W, Michel C, Sibomana M and Newport D F **(1997)** Exact and approximate rebinning algorithms for 3-D PET data. *IEEE Trans. Med. Imag*ing, MI-16: 145-158.
[Gem84] Geman S and Geman D **(1984)** Stochastic relaxation, Gibbs distributions, and the Bayesian restoration of images. *IEEE Trans PAMI*, 6: 721-741.
[Gem85] Geman S. and McClure D **(1985)** Bayesian image analysis: an application to single photon emission tomography. *in Proc. American Statistical Society, Statistical Computing Section (Washington, DC)* 12-18.
[GEMS] General Electric Medical Systems homepage http://www.gems.com.
[Gre90] Green P J **(1990)** Bayesian reconstruction from emission tomography data using a modified EM algorithm. *IEEE Trans. Med. Imaging*, MI-9: 84-93.
[Heb89] Hebert T J and Leahy R M **(1989)** A generalized EM algorithm for 3-D Bayesian reconstruction from Poisson data using Gibbs priors. *IEEE Trans. Med. Imaging*, MI-8: 194-202.

[Her80] Herman G T **(1980)** Image Reconstruction from Projections: The fundamentals of Computational Tomography. *Academic Press, New York.*

[Hud94] Hudson H M and Larkin R S **(1994)** Accelerated image reconstruction using ordered subsets of projection data. *IEEE Trans. Med. Imaging*, MI-13: 601-609.

[Jac99] Jacobson M, Levkovitz R, Ben-Tal A, Thielemans K, Spinks T, Belluzzo D, Pagani E, Bettinardi V, Gilardi M C, Zverovich A and Mitra G **(1999)** Enhanced 3D PET OSEM Reconstruction using inter-update Metz filters. in Press in *Phys. Med. Biol.*

[Kin89] Kinahan P E and Rogers J G **(1989)** Analytic 3D image reconstruction using all detected events. *IEEE Trans. Nucl. Sci.*, 36: 964-968.

[Lal93] Lalush D S and Tsui M W **(1993)** A general Gibbs prior for Maximum a posteriori reconstruction in SPET. *Phys. Med. Biol.*, 38: 729-741.

[Lan90] Lang K **(1990)** Convergence of EM Image reconstruction algorithms with Gibbs smoothing. *IEEE Trans. Med. Imaging*, MI-9: 4.

[Mus01a] S. Mustafovic, K.Thielemans, D. Hogg and P. Bloomfield **(2001)** *Object Dependency of Resolution and Convergence Rate in OSEM with Filtering,* proc. of 3D-2001 conference.

[Mus01b] S. Mustafovic, K.Thielemans, D. Hogg and P. Bloomfield **(2001)** *Object Dependency of Resolution and Convergence Rate in OSEM with Filtering*, proc. of IEEE Medical Imaging Conf. 2001.

[Mar99] Margalit T, Gordon E, Jacobson M, Ben-Tal A, Nemirovski A, Levkovitz R **(1999)** The ordered sets mirror descent and conjugate barrier optimization algorithms adapted to the 3D PET reconstruction problem. Submitted to *IEEE Trans. Med. Im.*aging.

[Nem78] Nemirovski A and Yudin D **(1978)** Problem complexity and method efficiency in optimization. *Nauka Publishers, Moscow, 1978 (in Russian); English translation: John Wiley & Sons, 1983.*

[Rea98a] Reader A J, Erlandsson K, Flower M A and Ott R J **(1998)** Fast accurate iterative reconstruction for low statistics positron volume imaging. *Phys. Med. Biol.*, 43: 835-846.

[Rea98b] Reader A J, Visvikis A, Erlandsson K, Ott R J, and Flower M A **(1998)** Intercomparison of four reconstruction techniques for positron volume imaging with rotating planar detectors. *Phys. Med. Biol.*, 43: 823-34.

[She82] Shepp L A and Vardi Y **(1982)** Maximum likelihood reconstruction for emission tomography. *IEEE Trans. Med. Imaging*, 1: 113-122.

[Sil90] Silverman B W, Jones M C, Wilson J D, and Nychka D W **(1990)** A smoothed EM approach to indirect estimation problems, with particular reference to stereology and emission tomography. *J. Roy. Stat. Soc.*, 52: 271-324.

[Sli98] Slijpen E T P, Beekman F J **(1998)** Comparison of post-filtering and filtering between iterations for SPECT reconstruction. *in Proc. IEEE Nucl. Sci. Symp. and Med. Imaging Conf.*, 2: 1363-6.

[Thi06] Thielemans, K., Manjeshwar, R. M., Xiaodong T., and Asma E. **(2006)**, Lesion detectability in motion compensated image reconstruction of respiratory gated PET/CT. *2006 IEEE Nuclear Science Symposium and Medical Imaging Conference* 3278-3282. [Thi99] Thielemans K, Jacobson M W, Belluzzo D

(1999) On various approximations for the projectors in iterative reconstruction algorithms for 3D-PET. *in Proceedings of the 3D99 Conference, Egmond Aan Zee*, (June 1999): 232-235. [Thi12] Kris Thielemans, Charalampos Tsoumpas, Sanida Mustafovic, Tobias Beisel, Pablo Aguiar, Nikolaos Dikaios, and Matthew W Jacobson, *STIR: Software for Tomographic Image Reconstruction Release 2*, Physics in Medicine and Biology, 57 (4), 2012 pp.867-883. [Tso08] Tsoumpas C, Turkheimer F E, Thielemans K **(2008)**, Study of direct and indirect parametric estimation methods of linear models in dynamic positron emission tomography. *Med. Phys.* 35(4): p. 1299-1309. [Tso11] Tsoumpas, C., et al **(2011)**, The effect of regularisation in motion compensated image reconstruction. *IEEE Nucl Sci Symp Med Imaging Conf* .