

Fast Imaging Library

of the

National Center for Image-Guided Therapy



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1 The NC-IGT Fast Imaging Library

In MR imaging applications, the dominant constraint to image acquisition is *time*. As the field has matured, a number of methods have been developed to reduce the length of time needed to acquire an image by reducing the amount of data needed to reconstruct a clinically viable image. This reduction in acquired data requirements is achieved through encodings that are complementary to the fundamental Fourier encoding employed in MRI. This includes temporal-domain encodings, such as UNFOLD, and spatial-domain encodings, as in parallel MR imaging methods such as SENSE and GRAPPA.

This library of functions provides a number of reconstruction algorithms that accurately employ these advanced MR imaging methods. This includes

- UNFOLD
- Parallel Imaging Methods
 - SENSE
 - VD-SENSE
 - SPACE RIP

– GRAPPA

as well as a number of associated MR image reconstruction algorithms, including

- EPI Nyquist ghost correction
- Homodyne processing of partial-Fourier data
- Gradient field inhomogeneity correction (gradwarp)

As of version 0.96, the library is compatible with both GE and Siemens MR scanners. For GE MR scanners, file format support includes raw data output using the "P-file" format, and the "vrgf.dat" and "ref.dat" files to respectively correct for ramp-sampling and gradient-offset phase correction during EPI acquisitions.

This library was developed at the National Center for Image Guided Therapy by

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The FFT calculations are provided by the KISS FFT library.

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Length 2^N FFTs are handled by code derived from OOURA FFT:

```
Copyright (C) 1996-2001 Takuya OOURA
email: ooura -at- mmm -dot- t -dot- u-tokyo -dot- ac -dot- jp
      http://momonga.t.u-tokyo.ac.jp/~ooura/fft.html
You may use, copy, modify this code for any purpose and
without fee. You may distribute this ORIGINAL package.
```

With version 0.9, the library now contains multiple functions to compute the Singular Value Decomposition (SVD) of a matrix.

The core SVD functions are an implementation of the bilateral diagonalization approach first described by Golub et. al. This algorithm is known to be extremely stable, and is drawn from the Colorado School of Mines Center for Wave Propagation Seismic Un*x C library.

Copyright (c) Colorado School of Mines, 2007.

Credits: Ian Kay, Canadian Geological Survey, Ottawa, Ontario 1999.

This is a translation in C from code written in Fortran that appeared in NETLIB, EISPACK, and SLATEC collections that was itself a translation from an original Algol code that appeared in:

Golub, G. and C. Reinsch (1971) Handbook for automatic computation II, Linear Algebra, p 134-151. SpringerVerlag, New York.

See also discussions of a similar code in Numerical Recipes in C. svd_sort: Nils Maercklin, GeoForschungsZentrum (GFZ) Potsdam, Germany, 2001.

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To support both the image-phase-alignment and virtual-body-coil functions, a second SVD implementation using a Lanczos iterative algorithm is now included. For the purpose of estimating the singular vectors associated the largest singular value of large matrices, this Lanczos approach is significantly faster than the more stable bi-diagonalization approach.

This code is derived from the netlib SVDPACK, via the SVDLIBC library (<http://tedlab.mit.edu:16080/~dr/SVDLIBC/>), and modified to be thread-safe. This code is

(c) Copyright 2003, Douglas Rohde

adapted from SVDPACKC, which is

(c) Copyright 1993, University of Tennessee
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To support GROG functions, the library has begun to transition to Eigen3 for matrix decompositions since version 2.0. Version 2.0 uses eigen-3.1.4 (with the EIGEN_MPL2_ONLY flag), which is distributed under the MPL2 license:

```
// This Source Code Form is subject to the terms of the Mozilla  
// Public License v. 2.0. If a copy of the MPL was not distributed  
// with this file, You can obtain one at http://mozilla.org/MPL/2.0/.
```

2 Quick Start Guide

The goal of this guide is to get a new user of the Fast Imaging Library (FIL) up and running as quickly as possible, using provided demo programs.

2.1 Prerequisites

Currently [release 2.0], the library is available on Linux (both 64-bit and 32-bit), Windows (MSWin64), and Mac OS X (darwin-intel).

The library provides a binary file for the processing functions, with MEX files to call the functions from Matlab. Thus, a C compiler is required. The library has been tested with `gcc` on Linux and Mac OS X, and MS Visual Studio 2008 on Windows.

2.2 Setup

First, extract the library into a working directory. Below, we will refer to this directory as the `[igt_fil_basepath]`. This should create a directory tree that includes `./demos`, `./include`, `./lib`, and `./source_code/matlab` paths.

2.3 MEX file demos

2.3.1 Build the MEX files

MEX files are C programs that are callable from Matlab. The FIL distribution contains a number of examples in the `source_code/matlab/mex` directory. To set up MEX file use, do the following:

- `chdir` to `[igt_fil_basepath]/source_code/matlab/mex`
- compile each of the matlab functions by calling `builddall.m`

Examples of how to use the MEX functions are located in `[igt_fil_basepath]/demos/mex_demo/`

After a `cd` to this directory, be certain to add both the matlab script and the path MEX paths to the matlab path:

```
addpath <igt_fil_basepath>/source_code/matlab
addpath <igt_fil_basepath>/source_code/matlab/mex
```

The remaining portion of this section presents each the MEX demos in turn.

2.3.1.1 Loading the Demo Data all of the MEX demos use the same raw data. This can be read into Matlab via `readnd`

```
k = readnd('phantom.dat');
```

This should provide 8-channels of k-space data for a resolution phantom (acquired at 1.5T using a fast spin echo sequence).

2.3.1.2 Zero-pad k-space Demo (util_demo.m) The file `util_demo.m` provides a simple example on how to zero-pad an accelerated k-space data set. First, a sampling pattern is generated. The input sampling pattern is structured with each row containing a `ky-z` coordinate location. Since there is only one slice here, all of the `z` coordinates are the same. `ky` is subsampled by 2, capturing all 'odd' lines.

```
Yo = [ vec(1:2:256) ones(128,1) ];
```

This sampling pattern is then passed to the `kstretch` function via

```
ko = kstretch( Yo, squeeze(k(:,Yo(:,1),1)), [256 256 1] );
```

`ko` should now be a zero-padded version of the subsampled `k` data. This can be visualized using the following Matlab command:

```
pltcmplx( k(:, :, 1), ko(:, :, 1) );
```

2.3.1.3 Partial Fourier Demo (pF_demo.m) The library includes functions to perform homodyne detection/synchronization for partial-Fourier data sets (as per Noll, Nishimura, and Macovski. *IEEE Trans Medical Imaging*. 10(2):154-163, 1991). The MEX file `correct_pF` performs this process by calling the `partial_Fourier` :

```
Y = 1:146; % specify the lines to use
k0 = correct_pF( k(:,Y,1), [ 256 256 ], 1 ); % perform the correction
im(k0); % visualize the result
```

The 3rd argument of the MEX function can be used to switch between a (0) step filter or a (1) ramp filter. The step filter carries better SNR, while the ramp filter is more tolerant of k-space that is off-center.

2.3.1.4 Parallel Imaging Demo (pmri_demo.m) Three parallel imaging algorithms are included in the library: SENSE, GRAPPA, and SPACE RIP (see *Parallel Imaging Algorithms* for more details). This demo demonstrates each of them on the same data set. First, the data is loaded and a subsampling pattern is generated.

```

k = readnd('phantom.dat');

N = 256;

k = k( (size(k,1)-N)/2+(1:N), (size(k,1)-N)/2+(1:N), : );

% form a variable density sampling pattern, 4x-2x-1x, with 3x total
% acceleration (suitable for self-referenced reconstructions)
Z = zeros(N,1);
Z( 2:4:end) = 1;
Z( (N/2) + (-(N/8-2):2:(N/8)) ) = 1;
Z( (N/2) + (-(N/32-2):(N/32)) ) = 1;
Y = find(Z);

```

Next, coil sensitivity maps are generated from the subsampled data set:

```

% generate the coil sensitivity maps
W = geysers( k(Y, :, :), Y(:), [N N 8] );

```

Finally, images are formed from the subsampled data using various reconstruction algorithms.

- SPACE RIP, using the LSQR-Hybrid algorithm to perform automatic regularization.

```

% solve the system using LSQR-Hybrid space rip
Isrc = srslsqr( W, ifft(fftshift(k(Y, :, :), 2), [], 2), Y(:) );

```

- GRAPPA

```

% solve the system using GRAPPA
[Fg, Ig2] = grappa( size(W), k(Y, :, :), Y(:) );

```

Ig2 here is the root-sum-of-squares image. If phase needs to be retained, reconstruct the image using coil sensitivity maps instead:

```

Ig = sum( conj(W) .* ifft2(fftshift(fftshift(Fg, 1), 2)), 3 );

```

- RLS-GRAPPA

This algorithm performs the GRAPPA reconstruction in hybrid-space (ky-x) and employs an RLS adaptive filter to rapidly compute the reconstruction parameters. In certain cases, it is significantly faster than standard GRAPPA.

```

[Frlsg, Irlsg] = rlsgrappa_x( size(W), ifft(fftshift(k(Y, :, :), 2), [], 2), Y(:) );

```

- standard Cartesian SENSE

```

k2 = zeros(size(k));
k2( 1:4:end, :, : ) = k( 1:4:end, :, : ) * 4; % '*4' to compensate for the
                                           % sparse sampling
K2 = ifft2( fftshift(fftshift(k2,1),2) );
Ics = sense( permute(W,[2 1 3]), permute(K2,[2 1 3]), 4 ).';

```

- and Variable Density SENSE

```

% solve the system using a variable density SENSE reconstruction
k3 = prep_vds( Y(:, permute(k(Y, :, :), [2 1 3])), [256 256 8] );
k3 = permute( k3, [2 1 3] );

K3 = ifft2( fftshift(fftshift(k3,1),2) );

Ivdcs = sense( permute(W,[2 1 3]), permute(K3,[2 1 3]), 4 ).';

```

Finally, the results are displayed

```

im([ Ig Isr; Ics Ivdcs ]);

```

2.3.1.5 UNFOLD Demo (unfold_demo.m) UNFOLD employs temporal variations in the sampling pattern to encode aliasing artifacts and then filters the results to suppress the encoded artifacts.

This demo uses a temporal data set

```

a = readnd('zoomed.dat');

```

and all processing is done within the MEX file

```

z = unfold(a);
im([ a squeeze(z) ]);

```

2.4 Important Details

2.4.1 Indexing

To keep with standard C convention, all indexing in the library starts at zero. This is particularly important in regards to specifying which phase-encode lines are acquired. So, if in Matlab the phase encode list runs from [1 .. M], the same phase encode list in the library would run from [0 .. (M-1)]. The MEX functions provided with the library perform this transition automatically to give a transparent interface to Matlab.

2.4.2 Data Ordering

Except for certain parallel imaging functions, all of the data is ordered as `kx-ky-z-timeframe-coil`

The parallel imaging algorithms that do not follow this convention include

1. `self_ref_b1_via_geyser`
2. `grappa`
3. all `srip_` functions, such as `srip_lsqr_recon`

which are ordered `ky-kx-coil` for historical reasons. In short, if a function call does not include a temporal and/or Z component as an argument, then the data should be short-ordered, with the subsampled `ky` data as the first dimension.

2.4.3 Anatomy of a MEX file

Here we describe how the MEX files are structured, using `unfold.c` as an example.

- preamble: declare macros to give a rational name to the pointers associated with data input/output

```
//
#define K_IN      prhs[0]
#define FREQ_IN   prhs[1]
#define WIDTH_IN prhs[2]

//
#define K_OUT     plhs[0]
#define NY_OUT    plhs[1]
```

- sanity: check that the number of inputs/outputs conform

```
if (nrhs < 1) {
    mexPrintf("At least 1 input argument is required.");
    return;
} else if (nlhs > 2) {
    mexPrintf("Too many output arguments.");
    return;
}
```

- pre: copy the data from Matlab arrays into C data structures

```
tmpR = mxGetPr(K_IN);
tmpI = mxGetPi(K_IN);
szK = mxGetNumberOfDimensions(K_IN);
dimK = mxGetDimensions(K_IN);
```

```

if ( !mxIsDouble(K_IN) || !mxIsComplex(K_IN) ) {
    mexPrintf( "1st input: Need to declare a complex "
              " array for the input k-space data\n" );
    return;
} else {
    // header variables that need to be populated
    hdr.recon_filt = 0.1;          // Width of UNFOLD filters, in frac of bw
    // default values
    hdr.Nz_proc = 1;
    hdr.ncoils = 1;

    hdr.Ny_proc = dimK[0];
    hdr.Nx = dimK[1];
    if (szK == 2) {
        hdr.Ny_proc = 1;          // number of temporal frames to process
        hdr.Nf = dimK[1];
    } else if (szK == 3) {
        hdr.Nf = dimK[2];        // number of temporal frames to process
    } else if (szK == 4) {
        hdr.Nz_proc = dimK[2];
        hdr.Nf = dimK[3];        // number of temporal frames to process
    } else { // (szK == 5)
        hdr.Nz_proc = dimK[2];
        hdr.Nf = dimK[3];        // number of temporal frames to process
        hdr.ncoils = dimK[4];
    }
    hdr.Nf_proc = set_nfproc(hdr.Nf, 0);

    //
    // printf("sz = ");
    // for (cnt=0;cnt<szK;cnt++) {
    //     printf("%d ",dimK[cnt]);
    // }
    //
    prd = hdr.Nf * hdr.Nz_proc * hdr.Ny_proc * hdr.Nx * hdr.ncoils;

    data_in = (COMPLEX *) malloc( prd * sizeof(COMPLEX) );

    // mexPrintf("prd = %d\n",prd);

    for (cnt=0;cnt<prd;cnt++) {
        data_in[cnt].re = tmpR[cnt];
        data_in[cnt].im = tmpI[cnt];
    }
}

```

- process: perform the data processing (i.e. call FIL functions)

```

filter_dc = (float *) malloc(hdr.Nf_proc*sizeof(float));
filter_ny = (float *) malloc(hdr.Nf_proc*sizeof(float));
filter_dckey = (float *) malloc(hdr.Nf_proc*sizeof(float));
filter_dcny = (float *) malloc(hdr.Nf_proc*sizeof(float));
near_dc = (short *) malloc(hdr.Nf_proc*sizeof(short));

// Create plans for a 1D FFT along the time (or frequency) axis

```

```

fft_mgr_init( &mgr );

// Set-up the unfold filters
setup_unfold( &hdr, hdr.Nf_proc, filter_dc, filter_ny, filter_dkept,
              filter_dcnny,
              near_dc, &filt_w );

full = (COMPLEX *) malloc( hdr.Nf_proc * hdr.Nz_proc * hdr.Ny_proc * hdr.Nx
hdr.ncoils * sizeof(COMPLEX) );

synth_frames( hdr.ncoils, hdr.Nf, hdr.Nz_proc, hdr.Ny_proc, hdr.Nx,
              data_in, hdr.Nf_proc, full );

// FFT from time to temporal frequency domain, with plan ptf (forward)
fft_t( hdr.ncoils, hdr.Nf_proc, hdr.Nz_proc, hdr.Ny_proc, hdr.Nx,
       'f', &mgr, 0, full, full );

if (mode == 'l') {
    // Keep only the DC along temp. freq. domain
    unfold_filter( hdr.ncoils, hdr.Nf_proc, hdr.Nz_proc, hdr.Ny_proc,
                  hdr.Nx, filter_dkept, full );
} else if (mode == 'm') {
    // Filter out DC and Nyquist region (temp. freq. domain)
    unfold_filter( hdr.ncoils, hdr.Nf_proc, hdr.Nz_proc, hdr.Ny_proc,
                  hdr.Nx, filter_dcnny, full );
} else { // (mode == 'h')
    // Filter out Nyquist region (temp. freq. domain)
    unfold_filter( hdr.ncoils, hdr.Nf_proc, hdr.Nz_proc, hdr.Ny_proc,
                  hdr.Nx, filter_ny, full );
}

fft_t( hdr.ncoils, hdr.Nf_proc, hdr.Nz_proc, hdr.Ny_proc, hdr.Nx,
       'b', &mgr, 0, full, full );

```

- post: copy the output data from C data structures into Matlab arrays

```

sz[0] = hdr.Nx;
sz[1] = hdr.Ny_proc;
sz[2] = hdr.Nz_proc;
sz[3] = hdr.Nf_proc;
//
write_nd_data( "unf_out.nd", full, "dble", 4, sz );

if (nlhs>0) {

    sz[0] = hdr.Ny_proc;
    sz[1] = hdr.Nx;

    szK = mxGetNumberOfDimensions(K_IN);
    if (szK == 2) {
        scl = 2;
        sz[1] = hdr.Nf;
    } else if (szK == 3) {
        scl = 3;
        sz[2] = hdr.Nf;
    } else if (szK == 4) {

```

```

    scl = 4;
    sz[2] = hdr.Nz_proc;
    sz[3] = hdr.Nf;
} else if (szK == 5) {
    scl = 5;
    sz[2] = hdr.Nz_proc;
    sz[3] = hdr.Nf;
    sz[4] = hdr.ncoils;
}
K_OUT = mxCreateNumericArray( scl, sz,
                             mxDOUBLE_CLASS,
                             mxCOMPLEX);

tmpR = mxGetPr(K_OUT);
tmpI = mxGetPi(K_OUT);

prd = hdr.Nz_proc * hdr.Ny_proc * hdr.Nx ;

for (cntZ=0;cntZ<hdr.ncoils;cntZ++) {
    for (cnt=0;cnt<prd*hdr.Nf; cnt++) {
        tmpR[ cnt + cntZ*hdr.Nf*prd ] =
            full[ cnt + cntZ*hdr.Nf_proc*prd ].re;
        tmpI[ cnt + cntZ*hdr.Nf*prd ] =
            full[ cnt + cntZ*hdr.Nf_proc*prd ].im;
    }
}
}

```

2.5 C test files

2.5.1 DICOM editing demo

The code included in

```
demos/dicom_demo/
```

demonstrates how to edit the value associated with a specific DICOM tag in a file, and write out the new DICOM image file.

2.5.2 .nd to .png Demo

This function is designed to convert the FIL .nd output data files into an image viewable on any platform. It uses the PNG and ZLIB libraries to accomplish this. These libraries are standard on Linux and Mac OS X, but may need to be installed on Windows. To build them on Windows, do the following

- build ZLIB
 - download the ZLIB source distribution from <http://www.zlib.net>

- unzip the source into a working directory (say, C:\src)
- cd to the zlib directory, and compile using the command `nmake -f win32\Makefile.msc`

- build LIBPNG

- download the PNG source distribution from <http://www.libpng.org/pub/png/libpng.html>
- unzip the source into the working directory
- cd to the lpng directory, and compile using the command `nmake -f lpng/scripts/makefile.vcwin32`

Once the libraries are built, modify the `Makefile.win32` file in the `display` directory to point to the location of the ZLIB and LIBPNG library and header files. `nd2png` should then build properly.

2.5.3 Demo for simple display, using ImLib

ImLib is a general image loading and rendering library, designed to simplify the generating drawable in X-Windows systems. It is included by default in many Linux distributions. Source code for ImLib can be found here: <ftp://ftp.gnome.org/pub/GNOME/sources/imlib/1.9/>

This demo code included in the

```
./demos/display/
```

directory uses ImLib to load data from a file stored in the ND-data format, and displays the data in a simple viewer.

The display demos use an "X Server" for data display. This is available by default on Linux and Mac. For Windows, a free version is available here: <http://xming.sourceforge.net/>

Code is also included that links to ImageMagick to display a set of images. This code works on both Linux and Windows. To setup ImageMagick on Windows, either (1) download the latest binary version along with the MSVC 2008 Portability Pack, or (2) download the source and compile. [ImageMagick binaries are currently compiled with MSVC 2008, which uses 'manifests' to manage DLL linking order. VC++ 6 doesn't have this, so programs compiled in VC++ 6 but linked to the ImageMagick DLL's will show an "R6034 error" everytime the program runs.]

3 Matlab Scripts

A few Matlab scripts are included to provide an interface to the Fast Imaging Library functions

3.1 Data I/O scripts

3.1.1 read_dump

`read_dump.m`: This script is an interactive way to read in binary data, output by the function `dump_out`

3.1.2 readnd

`readnd.m`: This script reads in data that was output by `write_nd_data`

Usage:

```
A = readnd( filename );
```

- **filename** A string containing the filename to read.
- **A** A matrix holding the data in the file.

3.1.3 savend

`savend.m`: This script writes to disk a Matlab matrix in a format that is readable in C by the `read_nd_data` function.

Usage:

```
savend( filename, A, format );
```

- **filename** The name of the output file.
- **A** The Matlab variable to output.
- **format** One of the following 3-character strings: 'int' for integers, 'flt' for floating point numbers, or 'dbl' for double precision numbers.

3.2 Data visualization scripts

3.2.1 im

`im.m`: A graphical interface program to view image and k-space data. It accepts upto 4-dimensional data, and can display the magnitude, real, imaginary, or phase of the data. Also includes Linkoping's "GOP" colormap format to visualize magnitude and phase simultaneously.

3.2.2 pltcmplx

`pltcmplx.m`: A graphical interface to compare two or three complex valued matrices, plotting real/imag or magnitude/phase for each column of the data.

4 Module Index

4.1 Modules

Here is a list of all modules:

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5 Module Documentation

5.1 Artifact Suppression via UNFOLD

Functions

- `int filter_t_init (int n, int x, int y, int c, double *a, double *b, filter_t_obj *obj)`
- `int filter_t_quit (filter_t_obj *obj)`
- `int filter_t_step (filter_t_obj *obj, COMPLEX *dataI, COMPLEX *dataO)`
- `void prep_unfold_dc (short Nx, short N_acq, short Nf, short ncoils, fil_fft_mgr *mgr, KCOORD *kline_o, KCOORD *kline_e, short fr1, COMPLEX *data, COMPLEX *buf_lg, COMPLEX *buf_sm, float *filter_dc, float *filter_dckept, short *near_dc, short filt_w, short Nf_proc, KCOORD *kline_c, COMPLEX *data_dc)`
- `int set_nfproc (short Nf, short flag)`
- `void setup_unfold (SCAN_INFO *hdr_ptr, int Nt, float *filter_dc, float *filter_ny, float *filter_dckept, float *filter_dcnny, short *near_dc, short *filt_w_ptr)`
- `void synth_frames (short ncoils, short Nf, short Nz, short Ny, short Nx, COMPLEX *data_in, short Nf_proc, COMPLEX *data_out)`
- `void synth_frames_cine (short ncoils, short Nf_full, short fr1, short Nf, short N_acq, short Nx, short ky, KCOORD *kline_o, KCOORD *kline_e, COMPLEX *data_in, short Nf_proc, COMPLEX *data_out)`
- `void transfer_dc (short dir, short ncoils, short Nf, short Nz, short Ny, short Nx, short filt_w, short *near_dc, float *filter, COMPLEX *lg_array, COMPLEX *sm_array)`
- `void unfold_filter (short ncoils, short Nf, short Nz, short Ny, short Nx, float *filter, COMPLEX *data)`
- `void unfold_recombine (short Nx, short Ny_proc, short Nz_proc, short Nf_proc, short *near_dc, short filt_w, COMPLEX *dc, COMPLEX *full)`

5.1.1 Detailed Description

The UNFOLD approach employs temporal domain processing to suppress artifacts.

The method is described in "Unaliasing by Fourier-encoding the overlaps using the temporal dimension" (UNFOLD). Bruno Madore, Gary H. Glover, and Norbert J. Pelc. *Magn Reson Med.* 42(5):813-826, Nov 1999. [DOI]

5.1.2 Function Documentation

5.1.2.1 `int filter_t_init (int n, int x, int y, int c, double * a, double * b, filter_t_obj * obj)`

Parameters:

obj an FIL filter bank object.

dataI input data

dataO output data

5.1.2.4 void prep_unfold_dc (short *Nx*, short *N_acq*, short *Nf*, short *ncoils*, fil_fft_mgr * *mngr*, KCOORD * *kline_o*, KCOORD * *kline_e*, short *fr1*, COMPLEX * *data*, COMPLEX * *buf_lg*, COMPLEX * *buf_sm*, float * *filter_dc*, float * *filter_dkept*, short * *near_dc*, short *filt_w*, short *Nf_proc*, KCOORD * *kline_c*, COMPLEX * *data_dc*)

Prepare UNFOLD filter memory arrays

Parameters:

Nx Size in x direction.

N_acq Number of acquired ky-kz lines.

Nf Size time direction.

ncoils number of coils

kline_o Sampling function, odd time frames.

kline_e Sampling function, even time frames.

fr1 Whether 1st frame is considered even (0) or odd (1).

buf_lg Larger buffer, for processing.

buf_sm Smaller buffer, for processing.

filter_dc UNFOLD filter, DC region.

filter_dkept UNFOLD filter (1-filter_dc)

near_dc Frequencies around DC.

filt_w Width of DC region, in near_dc.

Nf_proc number of temporal frames, including synthetic

5.1.2.5 int set_nfproc (short *Nf*, short *flag*)

Find out how many frames should be used in the reconstruction. This must be an even number, and a smooth transition between 1st and last frame is desirable. To do so, temporary synthetic frames may have to be created. One has the option of a setting based on precision (larger *Nf_proc*, *flag*=0), or speed of reconstruction (smaller *Nf_proc*, *flag*=1).

Parameters:

Nf Number of time frames.

flag switch between speed vs. precision

With `flag = 1`, the return value is `(int) 2.0*ceil(Nf/2)`. This setting provides increased recon speed and decreased memory usage, i.e., smaller `Nf_proc` (e.g., for 5 frames 1-2-3-4-5, the reconstruction is done with 6 frames 1-2-3-4-5-4, where the 4th is repeated to make `Nf_proc` even).

With `flag = 0`, the return value is `2*Nf - 2`. This setting provides increased precision, by avoiding discontinuities between the first and last frame of the data to be processed (e.g., for 5 frames 1-2-3-4-5, the recon is done with 8 frames 1-2-3-4-5-4-3-2, where frames 2, 3 and 4 are repeated, the transition between 1st frame and last frame (frame #2) being presumably smooth).

5.1.2.6 `void setup_unfold (SCAN_INFO *hdr_ptr, int Nt, float *filter_dc, float *filter_ny, float *filter_dkept, float *filter_dcnny, short *near_dc, short *filt_w_ptr)`

Set-up parameters/filters specific to the UNFOLD algorithm.

Parameters:

- hdr_ptr* Structure with scan info.
- Nt* Number of time points.
- filter_dc* UNFOLD filter, DC region.
- filter_ny* UNFOLD filter, Ny region.
- filter_dkept* UNFOLD filter (1-filter_dc)
- filter_dcnny* UNFOLD filter (filter_dc*filter_ny)
- near_dc* Frequencies around DC.
- filt_w_ptr* Width of DC region, in near_dc.

5.1.2.7 `void synth_frames (short ncoils, short Nf, short Nz, short Ny, short Nx, COMPLEX *data_in, short Nf_proc, COMPLEX *data_out)`

Generate extra, synthetic time frames. This has two purposes: to make the number of phases even to insure alternation between the two sampling schemes, and to make the change between last and first frames smoother.

Parameters:

- ncoils* Number of receiver coils.
- Nf* Size time direction.
- Nz* Size in z direction.
- Ny* Size in y direction.

Nx Size in x direction.
data_in Data input, to be extended from *Nf* to *Nf_proc* frames.
Nf_proc New size along t, including synthetic frames.
data_out output data

5.1.2.8 void synth_frames_cine (short ncoils, short Nf_full, short fr1, short Nf, short N_acq, short Nx, short ky, KCOORD * kline_o, KCOORD * kline_e, COMPLEX * data_in, short Nf_proc, COMPLEX * data_out)

For a given *ky* line, generate extra (synthetic) time frames. This has two purposes: to make the number of phases even to insure alternation between the two sampling schemes, and to make the change between last and first frames smoother.

Parameters:

ncoils Number of receiver coils.
Nf_full Array size time direction.
Nf Data size, <= *Nf_full*.
N_acq Number of k lines per frame.
Nx Size in x direction.
ky *ky* line being treated.
data_in Data input, to be extended from *Nf* to *Nf_proc* frames.
Nf_proc New size along t, including synthetic frames.
data_out output data

5.1.2.9 void transfer_dc (short dir, short ncoils, short Nf, short Nz, short Ny, short Nx, short filt_w, short * near_dc, float * filter, COMPLEX * lg_array, COMPLEX * sm_array)

When DC and Nyquist frequencies are handled separately in an application of UNFOLD parad, this function can be used to copy the multi-frame DC data to a processing buffer.

Parameters:

dir Direction of transfer (-1 from large array to small, 1 from small to large).
ncoils Number of receiver coils.
Nf Size time direction.
Nz Size in z direction.
Ny Size in y direction.

Nx Size in x direction.
flt_w Number of entries in near_dc[]
near_dc Location of those frequencies that correspond to near-DC frequencies.
filter Weight to give to data while transferring it (only for dir=1, from small to large).
lg_array Array containing all temporal frequencies (length Nf along frequency axis).
sm_array Array containing only temporal frequencies near DC (length flt_w along frequency axis).

5.1.2.10 void `unfold_filter` (short *ncoils*, short *Nf*, short *Nz*, short *Ny*, short *Nx*, float **filter*, COMPLEX **data*)

Apply the UNFOLD filters to the data

Parameters:

ncoils Number of receiver coils. (dim 5)
Nf Size time direction. (dim 4)
Nz Size in z direction. (dim 3)
Ny Size in y direction. (dim 2)
Nx Size in x direction. (dim 1)
filter UNFOLD filter, applied along dim 4.
data Data to filter (inplace operation: output overwrites input). size: Nx-Ny-Nz-Nf-coil

5.1.2.11 void `unfold_recombine` (short *Nx*, short *Ny_proc*, short *Nz_proc*, short *Nf_proc*, short **near_dc*, short *flt_w*, COMPLEX **dc*, COMPLEX **full*)

Recombine the improved DC region in 'dc' (calculated with half the acceleration) to the rest of the bandwidth (calculated with full acceleration).

Parameters:

Nx Size in x direction.
Nf_proc Size time direction, including synthetic frames
near_dc Frequencies around DC.
flt_w Width of DC region, in near_dc.
dc Contains improved version of DC region.
full Contains rest of bandwidth (DC removed). The output overwrites the input values in 'full'.

5.2 CINE processing functions

Functions

- void calc_DC_for_b1 (short Nx, short N_acq, short Ny, short Nf, short fr1, short ncoils, KCOORD *kline_c, int *acq_record, COMPLEX *xkykz, COMPLEX *DC_xkykz)
- void nonlin_cphase (SCAN_INFO hdr, int *hb_length, float *acq_timing, float systole_thr)
- void puzzleout_cineacq (int *trig_rr, int *trig_seg, int *trig_slice, SCAN_INFO *hdr_ptr, KCOORD *kline_o, KCOORD *kline_e, int *hb_length, float *acq_timing)
- void read_ecg_info (char **ecgfile, SCAN_INFO *hdr_ptr, int *trig_rr, int *trig_seg, int *trig_slice, int pass)
- void retrosp_gating_interp (short ncoils, short Nf_intrp, short Nf, short N_lines, short Ny, short Nx, short k, short ky, float *cph_record, float *ph_recon, COMPLEX *current_line, COMPLEX *kcine)
- void sort_rds_data (short *rawdata, int z, SCAN_INFO hdr, float *acq_timing, COMPLEX *kspace_data)

5.2.1 Function Documentation

5.2.1.1 void calc_DC_for_b1 (short Nx, short N_acq, short Ny, short Nf, short fr1, short ncoils, KCOORD * kline_c, int * acq_record, COMPLEX * xkykz, COMPLEX * DC_xkykz)

Calculate the DC data to be used for self-calibration purposes.

Parameters:

Nx number of points along readout

N_acq number of acquired phase encodes

Ny resolution along phase encode dimension

Nf number of temporal frames

fr1 select whether the data should be considered as an odd (fr1=0) or even (fr1=1) temporal frame.

ncoils number of coils

kline_c a list of the acquired k-space lines

xkykz input data, size: Nx, N_acq, Nf, ncoils, Nz

DC_xkykz output coil sensitivity estimate, size: Nx,2*N_acq,1,ncoils

5.2.1.2 void `nonlin_cphase` (`SCAN_INFO` *hdr*, `int` * *hb_length*, `float` * *acq_timing*, `float` *systole_thr*)

Calculate cardiac phase, using a non-linear model whereby diastole data get stretched more than systole data, when accounting for arrhythmia.

Parameters:

hdr Pointer to the structure with scan info.

hb_length Length of each RR interval, in units of TR (output).

acq_timing Info regarding every single TR in the entire acquisition (0. ky, 1. linear cardiac phase, 2. slice, 3. frame number, 4. order within segment, 5. heartbeat number, 6. index in sampling function, 7. non-linear cardiac phase).

systole_thr Fraction of a (normal, or average) heartbeat considered to belong to systole.

5.2.1.3 void `puzzleout_cineacq` (`int` * *trig_rr*, `int` * *trig_seg*, `int` * *trig_slice*, `SCAN_INFO` * *hdr_ptr*, `KCOORD` * *kline_o*, `KCOORD` * *kline_e*, `int` * *hb_length*, `float` * *acq_timing*)

Figure out how the cine acquisition proceeded, based on the timing of the R waves, the sampling function, and scan parameters.

Parameters:

trig_rr Timing of R-waves, in units of TR.

trig_seg Segment being acquired in given RR.

trig_slice Slice being acquired in given RR.

hdr_ptr Pointer to the structure with scan info.

kline_o Sampling function, odd time frames.

kline_e Sampling function, even time frames.

hb_length Length of each RR interval, in units of TR (output).

acq_timing Info regarding every single TR in the entire acquisition (0. ky, 1. linear cardiac phase, 2. slice, 3. frame number, 4. order within segment, 5. heartbeat number, 6. index in sampling function, 7. non-linear cardiac phase).

5.2.1.4 void `read_ecg_info` (`char` ** *ecgfile*, `SCAN_INFO` * *hdr_ptr*, `int` * *trig_rr*, `int` * *trig_seg*, `int` * *trig_slice*, `int` *pass*)

First pass at reading the file, with ECG info, generated by the psd.

Parameters:

- ecgfile* Name of the ECG info file.
- hdr_ptr* Pointer to the structure where the info is to be stored.
- trig_rr* Timing of R-waves, in units of TR.
- trig_seg* Segment being acquired in given RR.
- trig_slice* Slice being acquired in given RR.
- pass* For pass = 1, just find how many entries there are. For pass = 2, actually read these entries and store in memory.

5.2.1.5 void retrosp_gating_interp (short *ncoils*, short *Nf_intrp*, short *Nf*, short *N_lines*, short *Ny*, short *Nx*, short *k*, short *ky*, float * *cph_record*, float * *ph_recon*, COMPLEX * *current_line*, COMPLEX * *kcine*)

Sort the data gathered by the raw data server.

Parameters:

- ncoils* Number of receiver coils.
- Nf_intrp* Size time direction, after.
- Nf* Size time direction, before.
- N_lines* Number of ky-kz lines.
- Ny* Size y/ky direction.
- Nx* Size in x/kx direction.
- k* Index for current line.
- ky* ky location for current line.
- cph_record* Record of cardiac phase.
- ph_recon* Phase values desired.
- current_line* One k-line worth of data.
- kcine* Array where to store result

5.2.1.6 void sort_rds_data (short * *rawdata*, int *z*, SCAN_INFO *hdr*, float * *acq_timing*, COMPLEX * *kpace_data*)

Sort the data gathered by the raw data server.

Parameters:

- rawdata* Raw data from the raw data server, for all slices.
- z* Slice to be sorted out.

hdr Scan info.

acq_timing Info regarding every single TR in the entire acquisition (0. ky, 1. linear cardiac phase, 2. slice, 3. frame number, 4. order within segment, 5. heartbeat number, 6. index in sampling function, 7. non-linear cardiac phase).

kspace_data Sorted data, for desired slice.

5.3 Fourier Transform Functions

An FFT resource manager and associated functions.

Functions

- int `fft1d` (void *args)
- int `fft_mgr_alloc_2dfft` (fil_fft_mgr *mgr, int M, int N, char direction)
- int `fft_mgr_alloc_fft` (fil_fft_mgr *mgr, int N, char direction)
- int `fft_mgr_init` (fil_fft_mgr *mgr)
- int `fft_mgr_quit` (fil_fft_mgr *mgr)
- void `fft_t` (short ncoils, short nf, short nz, short ny, short nx, char direction, fil_fft_mgr *mgr, short center, COMPLEX *data_in, COMPLEX *data_out)
- void `fft_x` (short ncoils, short Nf, int Nyz, short Nx, char dir, fil_fft_mgr *mgr, short center, COMPLEX *data)
- void `fft_y` (short ncoils, short nf, short nz, short ny, short nx, char direction, fil_fft_mgr *mgr, short center, COMPLEX *data)
- void `fft_z` (short ncoils, short nf, short nz, short ny, short nx, char direction, fil_fft_mgr *mgr, short center, COMPLEX *data_in, COMPLEX *data_out)
- int `fil_2dfft` (fil_fft_mgr *mgr, int M, int N, COMPLEX *data, char dir)
- int `fil_fft` (fil_fft_mgr *mgr, int N, COMPLEX *data, char dir, int unused)
- void `fil_fft_shift` (COMPLEX *data, int Nx, int Ny)

5.3.1 Detailed Description

An FFT resource manager and associated functions.

This suite of functions provides a resource manager for Fast Fourier Transforms, in order to alleviate memory management bookkeeping.

The use of NC-IGT Fast Imaging Library (FIL) FFT manager facilitates reuse of scratch buffers needed by the FFT functions. Scratch buffers can be allocated at the start of a program, and used by multiple functions afterwards. Calling an FFT function with an initialized manager will create scratch space if there is none pre-allocated. Furthermore, if the FFT engine changes in the future, these `fil_fft` calls will remain backwards compatible.

Usage:

```

#include "fil_fft.h"

fil_fft_mgr mgr;
COMPLEX *data;

fft_mgr_init( &mgr );

data = (COMPLEX *) malloc( 256 * sizeof(COMPLEX) );

...

fil_fft( &mgr, 256, data, 'f', 1 );

...

fft_mgr_quit( &mgr );

```

Each manager allocates space for upto 512 different length-plus-f/b combinations. If your program needs more than 512 different FFTs, then use additional managers.

5.3.2 Function Documentation

5.3.2.1 int fft1d (void * args)

Computes a 1D FFT

To call this function, first declare a variable to hold the function arguments:

```
fft1d_args args;
```

Then, populate the variable,

```

args.direction = 'f'; // FFT direction: 'f' or 'b'
args.data      = in;  // pointer to COMPLEX data to be transformed
args.n        = N;   // length of data buffer
args.buf      = buf; // pointer to temporary COMPLEX buffer
args.center   = 0;   // k-space center is in the middle of the data
args.mngr     = mgr; // a pointer to an FFT manager

```

Then call the function:

```
fft1d( (void *) &args );
```

This structure allows calls to `fft1d` to be multi-threaded.

Inverse FFTs are scaled by the length of the data vector, so that a 'round trip' of and FFT followed by an IFFT will leave the data at the same amplitude.

Parameters:

args a pointer to an `fft1d_args` variable

5.3.2.2 int fft_mgr_alloc_2dfft (fil_fft_mgr * mgr, int M, int N, char direction)

Allocate an manager object for 2D FFTs.

Parameters:

mgr an fil_fft manager
M length of dim 1
N length of dim 2
direction 'f':forward FFT :: 'b':inverse FFT

5.3.2.3 int fft_mgr_alloc_fft (fil_fft_mgr * mgr, int N, char direction)

Allocate an manager object for 1D FFTs.

Parameters:

mgr an fil_fft manager
N length of requested fft
direction 'f':forward :: 'b':inverse

5.3.2.4 int fft_mgr_init (fil_fft_mgr * mgr)

Initialize the FFT manager.

The number of different FFT sizes needs to be declared before calling this initialization function.

Usage:

```
fil_fft_mgr mgr;  
  
fft_mgr_init( &mgr );
```

Parameters:

mgr a pointer to a FFT manager

5.3.2.5 int fft_mgr_quit (fil_fft_mgr * mgr)

Free all FFT-related memory allocations, and release the manager.

Parameters:

mgr an FFT manager

5.3.2.6 void `fft_t` (short *ncoils*, short *nf*, short *nz*, short *ny*, short *nx*, char *direction*, `fil_fft_mgr` * *mngr*, short *center*, COMPLEX * *data_in*, COMPLEX * *data_out*)

FFT from time to frequency, or vice-versa. The input is a dataset ordered (nx -x- ny -x- nz -x- nf -x- ncoils), and the FFT is performed only in the temporal frequency direction (2nd dimension).

Parameters:

ncoils Number of coils. (dim 5)

nf Number of time frames. (dim 4)

nz Size along kz. (dim 3)

ny Size along ky. (dim 2)

nx Size along x or kx. (dim 1)

direction 'f' : forward FFT, or 'b' : inverse FFT

mngr a pointer to an FFT manager

center is center of k-space in the center of the data? set to 0 if DC is at 0, otherwise DC assumed to be at $nf/2$

data_in Input data

data_out Output data. If it is the same as *data_in*, input data simply gets overwritten.

5.3.2.7 void `fftx` (short *ncoils*, short *Nf*, int *Nyz*, short *Nx*, char *dir*, `fil_fft_mgr` * *mngr*, short *center*, COMPLEX * *data*)

FFT along x or kx. The input is a data-set ordered (Nx -x- ($Ny*Nz$) -x- Nf -x- *ncoils*), and an FFT is performed only in the x/kx direction.

Parameters:

ncoils number of coils

Nf size in the temporal frame direction.

Nyz size in the Nyz direction.

Nx size in the x/kx direction.

dir 'f' : forward FFT, or 'b' : inverse FFT

mngr a pointer to an FFT manager

center 0 if DC is at (0,0), otherwise DC assumed to be at ($Nx/2, Nyz/2$)

data Data to FFT. The input data gets overwritten by the output data.

5.3.2.8 void ffty (short *ncoils*, short *nf*, short *nz*, short *ny*, short *nx*, char *direction*, fil_fft_mgr * *mngr*, short *center*, COMPLEX * *data*)

FFT along y or ky. The input is a data-set ordered (nx -x- ny -x- nz -x- nf -x- ncoils), and an FFT is performed only in the y/ky direction.

Parameters:

ncoils Number of coils. (dim 5)

nf Number of time frames. (dim 4)

nz Size along kz. (dim 3)

ny Size along ky. (dim 2)

nx Size along x or kx. (dim 1)

direction 'f' : forward FFT, or 'b' : inverse FFT

mngr a pointer to an FFT manager

center 0 if DC is at (0,0), otherwise DC assumed to be at (Nx/2,Ny/2)

data Data to FFT. The input data gets overwritten by the output data.

5.3.2.9 void fftz (short *ncoils*, short *nf*, short *nz*, short *ny*, short *nx*, char *direction*, fil_fft_mgr * *mngr*, short *center*, COMPLEX * *data_in*, COMPLEX * *data_out*)

FFT along z or kz. The input is a data-set ordered as (nx -x- ny -x- nz -x- nf -x- ncoils), and an FFT is performed only in the z/kz direction.

Parameters:

ncoils Number of coils. (dim 5)

nf Number of time frames. (dim 4)

nz Size along kz. (dim 3)

ny Size along ky. (dim 2)

nx Size along x or kx. (dim 1)

direction 'f' : forward FFT, or 'b' : inverse FFT

mngr a pointer to an FFT manager

center 0 if DC is at (0,0), otherwise DC assumed to be at (Nx/2,Ny/2)

data_in Input data

data_out Output data. If it is the same as *data_in*, input data simply gets overwritten.

5.3.2.10 int fil_2dfft (fil_fft_mgr * mgr, int M, int N, COMPLEX * data, char dir)

Perform a 2D FFT on the `data`.

Note: to match Matlab's "ifft2", the output must be scaled by $1/(M*N)$.

Parameters:

- mgr* an FFT manager
- M* dim-1 length of the data set
- N* dim-2 length of the data set
- data* a pointer to the data buffer to transform
- dir* FFT direction forward "f" or backward "b"

5.3.2.11 int fil_fft (fil_fft_mgr * mgr, int N, COMPLEX * data, char dir, int unused)

Perform a 1D FFT on the `data`.

Note: consistent with the underlying FFT engines used in this function, the inverse FFT (when `dir = 'b'`) is *not* scaled to unity.

Parameters:

- mgr* an FFT manager
- N* the length of the data set
- data* a pointer to the data buffer to transform
- dir* FFT direction forward 'f' or backward 'b'
- unused* (unused)

5.3.2.12 void fil_fft_shift (COMPLEX * data, int Nx, int Ny)

Perform an FFT shift on the `data`, swapping the 1st/3rd and 2nd/4th quadrants of the data space.

Parameters:

- data* pointer to the input data
- Nx* dim 1 of the data
- Ny* dim 2 of the data

5.4 DICOM File Utilities

Functions

- void edit_dicom (LIST_NODE *list, short tag0, short tag1, char *filename, char *im_hdr, int *hdrsize_ptr, void *newvalue, short newvalue_length)
- void eval_dicom (LIST_NODE *list, short tag0, short tag1, char *filename, char *value, char *value_type, short max_length)
- LIST_NODE find_tag (LIST_NODE *list, short tag0, short tag1)
- void get_dicom_info (char *filename, LIST_NODE *list, short Nmax)
- int is_dicom (char *filename)
- void print_list (LIST_NODE *list, char *filename)
- short write_ima (SCAN_INFO hdr, short flip_h, short flip_v, short rot_90, char **imfile, int imnum, int z_anat, COMPLEX *buf, COMPLEX *result, char *path_out)

5.4.1 Detailed Description

A set of functions to read/edit/write DICOM headers and files.

The model followed by these functions is the following:

- The DICOM header information is read for a file
- The header is parsed to construct a dictionary (the 'list')
- For requests for tag values, the tag location is determined from the list, and the value is determined from the file itself.
- The edit tag function should be used primarily for changing the value of an existing tag, e.g. to change the image number.
- Writing a new DICOM file consists of writing the header information, followed by the image data itself.

Testing has been done with DICOM files generated by GE scanners.

5.4.2 Function Documentation

5.4.2.1 void edit_dicom (LIST_NODE * list, short tag0, short tag1, char * filename, char * im_hdr, int * hdrsize_ptr, void * newvalue, short newvalue_length)

Change the value of one entry, in a DICOM header.

Parameters:

list List of DICOM entries.

tag0 Specific tag. first 16 bits of the tag,
tag1 the second set of 16 bits of the tag.
filename Name of DICOM file, where im_hdr comes from.
im_hdr DICOM header, stored in a char array.
hdrsize_ptr The size of the DICOM header. If editing the header changes the size, the new size is returned.
newvalue New value to be inserted in header.
newvalue_length Length in bytes of newvalue. Unless this is a char string, this info tends to be redundant with newvalue_type.

5.4.2.2 void eval_dicom (LIST_NODE * list, short tag0, short tag1, char * filename, char * value, char * value_type, short max_length)

Find the value of one particular DICOM entry.

Parameters:

list List of DICOM entries.
tag0 A Specific tag. tag0 contains the first 16 bits
tag1 tag1 contains the 2nd set of 16 bits
filename Name of DICOM file.
value Pointer to where the value should be written.
value_type String giving the variable type expected (char, float, double, long, ulong, short, ushort)
max_length Maximum length, in bytes, to be written out (i.e., size allocated at the address 'value'.

5.4.2.3 LIST_NODE find_tag (LIST_NODE * list, short tag0, short tag1)

In a list of DICOM entries, finds a given tag, and return the associated entry. The returned entry contains the info on where (offset), how (VR) and how much (length) should be read, to get the value associated with the tag.

Returns:

DICOM entry relating to this tag, extracted from the list of all entries.

Parameters:

list List of DICOM entries.
tag0 Specific tag. tag0 contains the first 16 bits,
tag1 tag1 the second set of 16 bits.

5.4.2.4 void get_dicom_info (char *filename, LIST_NODE *list, short Nmax)

Takes a DICOM file, and extracts all the tags. Each entry includes the tag number, the VR associated with the tag, the length of the value field, and the offset in bytes from the beginning of the file to the value field.

Parameters:

filename Name of DICOM file.

list List of tag entries extracted from file.

Nmax maximum number of entries to be considered (proportional to the amount of memory allocated for the list).

5.4.2.5 int is_dicom (char *filename)

Returns 1 if the file is a DICOM file and 0 otherwise.

Parameters:

filename Name of DICOM file

5.4.2.6 void print_list (LIST_NODE *list, char *filename)

Print out a list of all DICOM tags in a file, along with VR values, offset values, the length of the value field and the actual value. The 'list' was first built using get_dicom_info().

Parameters:

list List of DICOM entries.

filename Name of DICOM file.

5.4.2.7 short write_ima (SCAN_INFO hdr, short flip_h, short flip_v, short rot_90, char **imfile, int imnum, int z_anat, COMPLEX *buf, COMPLEX *result, char *path_out)

Finish cropping, rotating, flipping, shifting the result, and write it out as a dicom file.

Parameters:

hdr header information, associated with *buf

flip_h Flag to flip horizontally.

flip_v Flag to flip vertically.

rot_90 Flag to rotate +90 (=+1) or -90 (= -1) degrees.
infile input DICOM file, for header information
imnum Number of the slice being written out (between 1 and Nz).
z_anat Current z loc, anatomical ordering
buf input data
result Reconstructed image data
path_out Directory where to write result.

5.5 GradWarp Functions

Functions

- void gwarp_apply2 (float W[], float hpp[], float vpp[], float *hpixs, float *vpixs, int N_h, int N_v, float mag[])
- void gwarp_calc (float *tl, float *tr, float *br, float *bl, int N_h, int N_v, float hpixs[], float vpixs[], float *d, float *u, float W[], float hpp[], float vpp[], char *fname)
- void gwarp_prep (float tl[], float tr[], float br[], float bl[], int N_h, int N_v, float hpixs[], float vpixs[], float d[], float u[])
- int gwarp_read_parms (char *fname, GWARP_PARMS *gwp)

5.5.1 Function Documentation

5.5.1.1 void gwarp_apply2 (float W[], float hpp[], float vpp[], float * hpixs, float * vpixs, int N_h, int N_v, float mag[])

Parameters:

W the weighting factor
hpp unwarped location in the horizontal direction
vpp unwarped location in the vertical direction
hpixs locations along the horizontal axis where pixels are found
vpixs locations along the vertical axis where pixels are found
N_h Number of pixels in horizontal direction
N_v number of pixels in vertical direction
mag image data

5.5.1.2 void gwarp_calc (float * *tl*, float * *tr*, float * *br*, float * *bl*, int *N_h*, int *N_v*, float *hpixs*[], float *vpixs*[], float * *d*, float * *u*, float *W*[], float *hpp*[], float *vpp*[], char * *fname*)

outputs: *W*, *hpp*, *vpp*

Parameters:

tl (unused) top left coordinate (x,y,z), in cm
tr (unused) top right coordinate (x,y,z), in cm
br (unused) bottom right coordinate (x,y,z), in cm
bl bottom left coordinate (x,y,z), in cm
N_h Number of horizontal
N_v number of vertical
hpixs horizontal pixels (length = *N_out*)
vpixs vertical pixels (length = *N_out*)
d scale factors (length = 2)
u unit vector directions (length = 6)
W the weighting factor (length = *N_h***N_v*)
hpp unwarped location in the horizontal direction (length = *N_h***N_v*)
vpp unwarped location in the vertical direction (length = *N_h***N_v*)
fname input filename for the gradwarp spherical harmonic correction coefficients.
Set to NULL if unavailable.

5.5.1.3 void gwarp_prep (float *tl*[], float *tr*[], float *br*[], float *bl*[], int *N_h*, int *N_v*, float *hpixs*[], float *vpixs*[], float *d*[], float *u*[])

compute the 'd' and 'u' vectors, based on the size of the FOV and the number of pixels along each image dimension.

Parameters:

tl top left coordinate (x,y,z), in cm
tr top right coordinate (x,y,z), in cm
br bottom left coordinate (x,y,z), in cm
bl bottom right coordinate (x,y,z), in cm
N_h Number of h
N_v Number of v
hpixs locations along the horizontal axis where pixels are found
vpixs locations along the vertical axis where pixels are found

5.5.1.4 int gwarp_read_parms (char * *fname*, GWARP_PARMS * *gwp*)

Function to parse the GE gradwarp spherical harmonic correction file.

Parameters:

- fname* input filename
- gwp* the destination, structure of gradwarp parameters

5.6 Image Manipulation Functions

Routines to scale, interpolate, flip, and rotate images.

Functions

- void find_annotation (int slice, float loc0, char ras0, float slthick, float scanspacing, int locs_brth, int *rot3, float *ctr, float tloc0, float tloc1, float *loc_ptr, char *ras_ptr)
- void interplin_ima (short Nx, short Ny, short Ny_int, short N_out, float off_phdir, COMPLEX *data, float *data_int)
- void interpsinc_ima (short Nx, short Ny, short Ny_int, short N_out, float off_phdir, COMPLEX *data, float *data_int)
- void orientation (float x_tl, float y_tl, float z_tl, float x_tr, float y_tr, float z_tr, float x_br, float y_br, float z_br, int *rot1, int *rot2, int p_pos, int p_entry, short *flip_h_ptr, short *flip_v_ptr, short *rot_90_ptr)
- void rot_and_flip (short rot_90, short flip_h, short flip_v, short N_out, float *im_out)
- short rot_and_flip_data_obj (short rot_90, short flip_h, short flip_v, DATA_OBJ *obj)

5.6.1 Detailed Description

Routines to scale, interpolate, flip, and rotate images.

5.6.2 Function Documentation

5.6.2.1 void find_annotation (int *slice*, float *loc0*, char *ras0*, float *slthick*, float *scanspacing*, int *locs_brth*, int * *rot3*, float * *ctr*, float *tloc0*, float *tloc1*, float * *loc_ptr*, char * *ras_ptr*)

Figure out the location and RAS (1 char for right vs anterior vs superior, for sagittal-like, coronal-like or axial-like planes respectively). This is used for image annotation, e.g., I5.2 would be an axial-like plane 5.2 mm from isocenter, in the inferior direction.

Parameters:

- slice* Number of the slice being treated (between 1 and N_sl).
- loc0* Location of first slice.
- ras0* Axis for value loc0.
- slthick* Slice thickness (mm).
- scanspacing* Spacing between slices (mm).
- locs_brth* Number of slices acquired per breathold duration.
- rot3* Third line of rotation matrix, i.e. through slice direction.
- ctr* 3 element position vector for FOV center.
- tlloc0* Distance from isocenter, as expressed in the epic code in `rsp_info[0].rsptloc`, for the first slice.
- tlloc1* Distance from isocenter, in `rsp_info[0].rsptloc`, for the 2nd slice.
- loc_ptr* Location of current slice.
- ras_ptr* Axis for value loc.

5.6.2.2 void interplin_ima (short Nx, short Ny, short Ny_int, short N_out, float off_phdir, COMPLEX * data, float * data_int)

Interpolate (linearly) the reconstruction image to the image size expected by GE's Signa display tools, and shift by prescribed amount in phase-encoding direction.

(Note: phase information is discarded)

5.6.2.3 void interpsinc_ima (short Nx, short Ny, short Ny_int, short N_out, float off_phdir, COMPLEX * data, float * data_int)

Interpolate (using a sinc function) image to the image size expected by GE's Signa display tools, and shift by prescribed amount in phase-encoding direction.

(Note: phase information is discarded)

5.6.2.4 void orientation (float x_tl, float y_tl, float z_tl, float x_tr, float y_tr, float z_tr, float x_br, float y_br, float z_br, int * rot1, int * rot2, int p_pos, int p_entry, short * flip_h_ptr, short * flip_v_ptr, short * rot_90_ptr)

Determine if the output needs to be rotated and/or flipped.

Parameters:

- x_tl* Coordinates for top left corner
- x_tr* Coordinates for top right corner
- x_br* Coordinates for bottom right corner

rot1 First line of rotation matrix, i.e. frequency-encoding direction.
rot2 Second line of rotation matrix, i.e. phase-encoding direction.
p_pos Patient position (1 for supine, 2 for prone, 4 for left decub, 8 for right decub).
p_entry Patient entry ('1' for head first, '2' for feet first).
flip_h_ptr Flag to flip horizontally.
flip_v_ptr Flag to flip vertically.
rot_90_ptr Flag to rotate +90 (=+1) or -90 (=-1)

5.6.2.5 void rot_and_flip (short rot_90, short flip_h, short flip_v, short N_out, float * im_out)

Rotate and/or flip a square magnitude (i.e. not complex) image.

Parameters:

rot_90 Flag to rotate +90 (=+1) or -90 (=-1) degrees.
flip_h Flag to flip horizontally.
flip_v Flag to flip vertically.
N_out Dimension of square, output image.
im_out Magnitude image to rotate and/or flip.

5.6.2.6 short rot_and_flip_data_obj (short rot_90, short flip_h, short flip_v, DATA_OBJ * obj)

Rotate and/or flip any data object.

Parameters:

rot_90 Flag to rotate +90 (=+1) or -90 (=-1) degrees.
flip_h Flag to flip horizontally.
flip_v Flag to flip vertically.
obj image to rotate and/or flip. Image must be square, but can be any DATA_OBJ data type

5.7 Vendor Specific Functions: GE

Functions

- int apply_epi_phase_ge (COMPLEX *k, int xres, int yres, int ncoils, DATA_OBJ *refdat, int expidir)

- `int apply_vrgf_ge (COMPLEX *k, int nz, int *sz, char *fname, COMPLEX **ko)`
- `int correct_epi_phase_ge (COMPLEX *k, int xres, int yres, int ncoils, char *fname, int expidir)`
- `void correct_fcard (SCAN_INFO hdr, COMPLEX *kspace_data)`
- `int read_data_from_Pfile (SCAN_INFO *hdr, DATA_OBJ *rawframe, DATA_OBJ *vrgf, FILE *fid, char *buf, char *buf2, int slice, int vol, int nbaselines)`
- `short read_data_ge (char **Pnames, int z, SCAN_INFO hdr, KCOORD *kline, KCOORD *kline_o, KCOORD *kline_e, COMPLEX *kspace_data)`
- `short read_hdr_ge (char *Pname, SCAN_INFO *hdr_ptr)`
- `int read_vrgf_ge (char *fname, int Nx, char endian, DATA_OBJ *H)`

5.7.1 Detailed Description

Functions specific to GE MR scanners, mostly for reading files generated by GE scanners.

5.7.2 Function Documentation

5.7.2.1 `int apply_epi_phase_ge (COMPLEX *k, int xres, int yres, int ncoils, DATA_OBJ *refdat, int expidir)`

Applies EPI phase correction to the k-space data. The input data is assumed to be sized [ky kx c], where c can be coils, slices, etc. A linear and constant phase correction term should be provided in the 'refdat' object.

Parameters:

- k* input data to correct, of size [yres xres ncoils]
- xres* number of points along readout
- yres* number of points along phase-encode direction
- ncoils* number of frames/coils
- refdat* a data object derived from the ref.dat file
- expidir* the direction of the applied shift. Choices are limited to +1 or -1.

5.7.2.2 `int apply_vrgf_ge (COMPLEX *k, int nz, int *sz, char *fname, COMPLEX **ko)`

Applies the VRGF correction matrix to EPI k-space data, to compensate for ramp-sampling during acquisition.

The VRGF data matrix is applied only to the first two dimensions of the input k-space data, i.e. the same matrix is applied to all coils and/or time frames.

DEPRECATED: *this function is to be replaced by read_vrgf_ge and correct_rampsamp*

Parameters:

- k* input data to correct (output over-writes the input)
- nz* number of dimension to the data
- sz* an array holding the size of each data dimension. Holds the size of the output data matrix when the function successfully returns.
- fname* the filename holding the VRGF correction data (default: "vrgf.dat")
- ko* output data

5.7.2.3 int correct_epi_phase_ge (COMPLEX * *k*, int *xres*, int *yres*, int *ncoils*, char * *fname*, int *expidir*)

Applies EPI phase correction to the k-space data. The input data is assumed to be sized [ky kx c], where c can be coils, slices, etc. A linear and constant phase correction term is read from the supplied ref.dat file, and applied to both odd and even lines to align them.

Parameters:

- k* input data to correct (output over-writes the input)
- xres* number of points along readout
- yres* number of points along phase-encode direction
- ncoils* number of frames/coils
- fname* the filename holding the EPI phase correction data (default: "ref.dat")
- expidir* the direction of the applied shift. Choices are limited to +1 or -1.

5.7.2.4 void correct_fccard (SCAN_INFO *hdr*, COMPLEX * *kspace_data*)

Fastcard sequences skip the first view of each segment, for the first cardiac phase. The reason has to do with the time it takes to detect an R wave, and that it would already be too late to acquire the first view of the segment. Fill-in the missing data using closest-neighbours.

Parameters:

- hdr* Structure with scan info.
- kspace_data* Input k-space data.

5.7.2.5 int read_data_from_Pfile (SCAN_INFO * *hdr*, DATA_OBJ * *rawframe*, DATA_OBJ * *vrgf*, FILE * *fid*, char * *buf*, char * *buf2*, int *slice*, int *vol*, int *nbaselines*)

A function to read raw data from a GE P-file. Will return data corresponding to a specific slice or volume, if requested.

Parameters:

hdr the scan information associated with the data

rawframe the output data buffer to fill

vrgf the rampsamp correction data. set to NULL if not available or needed

fid FILE handle to read from

buf a pre-allocated scratch buffer of size: $2 * \text{hdr.Nsl} * \text{hdr.ncoils} * \text{hdr.frame_size} * (\text{hdr.Ny} + \text{nbaselines}) * \text{sizeof}(\text{short})$

buf2 a pre-allocated (COMPLEX *) scratch buffer of size: $\text{hdr.Nsl} * \text{hdr.ncoils} * \text{hdr.frame_size} * \text{hdr.Ny} * \text{sizeof}(\text{DATATYPE})$ DATATYPE is declared by the 'type' field of rawframe. It can be "flt" or "dbl" (the default)

slice the slice number to read. set to -1 to read all slices.

vol the volume number (time point) to read

5.7.2.6 short read_data_ge (char ** *Pnames*, int *z*, SCAN_INFO *hdr*, KCOORD * *kline*, KCOORD * *kline_o*, KCOORD * *kline_e*, COMPLEX * *kspace_data*)

Read the input k-space data from GE P-files, for cardiac applications with temporal encoding

Parameters:

Pnames an array of filename

hdr Structure with scan info.

kspace_data the returned k-space data

5.7.2.7 short read_hdr_ge (char * *Pname*, SCAN_INFO * *hdr_ptr*)

Read the image scan header from a GE P file to find relevant imaging information.

Parameters:

Pname Name of the P file containing the header to be read.

hdr_ptr Pointer to the structure where the info is to be stored.

5.7.2.8 int read_vrgf_ge (char * *fname*, int *Nx*, char *endian*, DATA_OBJ * *H*)

read in the GE ramp-sampling correction file. Use correct_rampsamp to apply to the measured data.

Parameters:

fname the filename holding the VRGF correction data (default: "vrgf.dat" if passed a NULL)

Nx length of readout data

endian endian-ness of the vrgf.dat file {'l','b'} [little-endian by default]

H the data object for the ramp-sampling correction operator. Memory will be allocated if the H.data memory is NULL.

5.8 Vendor Specific Functions: Siemens

Functions

- int parse_vrgf_siemens (char **fname*, DATA_OBJ **H*)
- int read_data_from_measdat (SCAN_INFO **hdr*, DATA_OBJ **rawframe*, DATA_OBJ **vrgf*, FILE **fid*, char **buf*, char **buf2*, int *slice*, int *vol*, int *ngc_flag*)

5.8.1 Detailed Description

Functions specific to Siemens MR scanners, mostly for reading data files generated by Siemens scanners.

5.8.2 Function Documentation

5.8.2.1 int parse_vrgf_siemens (char * *fname*, DATA_OBJ * *H*)

parse the meas*.dat file, and compute the ramp-sampling regridding operator

Parameters:

fname the filename for the EPI data (or data descriptor file)

H the data object for the ramp-sampling correction operator. Memory will be allocated if the H.data memory is NULL.

5.8.2.2 int read_data_from_measdat (SCAN_INFO * *hdr*, DATA_OBJ * *rawframe*, DATA_OBJ * *vrgf*, FILE * *fid*, char * *buf*, char * *buf2*, int *slice*, int *vol*, int *ngc_flag*)

A function to read raw data from a Siemens meas_*.dat file. Will return data corresponding to a specific slice or volume, if requested.

```
&& (chn_num == (hdr->ncoils-1)) {
```

```
&& (chn_num == (hdr->ncoils-1)) {
```

Parameters:

hdr the scan information associated with the data

rawframe the output data buffer to fill

vrgf the rampsamp correction data. set to NULL if not available or needed

fid FILE handle to read from

buf a pre-allocated scratch buffer of size: 2 * *hdr.Nsl* * *hdr.ncoils* * *hdr.frame_size* * (*hdr.Ny*+*nbaselines*) * sizeof(float)

buf2 a pre-allocated (COMPLEX *) scratch buffer of size: *hdr.Nsl* * *hdr.ncoils* * *hdr.frame_size* * *hdr.Ny* * sizeof(DATATYPE) DATATYPE is declared by the 'type' field of *rawframe*. It can be "flt" or "dbl" (the default)

slice the slice number to read. set to -1 to read all slices.

vol the volume number (time point) to read. (multiple calls to this function are needed to read all volumes)

ngc_flag for EPI data, set to 1 in order apply internal ghost correct using pre-echo-train data. (default: 0==off) *

5.9 Linear System Solvers

standard numerical solutions to linear system problems

Functions

- double * alloc1double (size_t n1)
- double ** alloc2double (size_t n1, size_t n2)
- void cgsolv (COMPLEX *A, int n, COMPLEX *b, COMPLEX *x, int k_max, double thresh)
- void compute_pinv (double **u, double w[], double **v, short n, short m, double **S_inv)
- int compute_svd (double **a, int m, int n, double w[], double **v)
- void free1double (double *p)
- void free2double (double **p)

- `int lsv (COMPLEX *A, int m, int n, COMPLEX *x0, double *sigma, COMPLEX *v, float thresh)`
- `int rank_one_est (COMPLEX *C, float *mask, int Nx, int Ny, double *d, COMPLEX *u, COMPLEX *v, int tid)`
- `void svd_backsubstitute (double **u, double w[], double **v, int n, int m, double b[], double x[])`
- `void svd_sort (double **u, double *w, double **v, int m, int n)`

5.9.1 Detailed Description

standard numerical solutions to linear system problems

A linear of system of equations can be ordered as

$$Ax = b$$

where A is a system matrix of size m -by- n , b is a vector of measured data, and x is the solution vector—which after solution describes a linear combination of values from A to form b .

5.9.2 Function Documentation

5.9.2.1 `double* alloc1double (size_t n1)`

1D vector memory allocation for SVD routines

5.9.2.2 `double** alloc2double (size_t n1, size_t n2)`

2D array allocation, e.g. $A[][]$, for SVD routines.

5.9.2.3 `void cgsolv (COMPLEX * A, int n, COMPLEX * b, COMPLEX * x, int k_max, double thresh)`

Generic CG solver

Solves the problem $Ax = b$ using the method of conjugate gradients. A must be conjugate symmetric, which implies that x and b are vectors of equal length, n .

Design based on the practical CG algorithm in “Matrix Computations” by Golub and Van Loan.

One can specify either a fixed number of iterations, or a residual error stopping criterion. To use the default values, ($k_max = 20$, $thresh = 1e-9$), declare '0' as the input values for k_max and $thresh$.

Parameters:

- A* system matrix, must be complex-conjugate symmetric
- n* length of data vector
- b* objective vector
- x* solution
- k_max* maximum number of iterations
- thresh* residual error threshold

5.9.2.4 void compute_pinv (double ** u, double w[], double ** v, short n, short m, double ** S_inv)

Computes the inverse of the sensitivity matrix, using the output of compute_svd(). It is given by *v* times the singular values *w* and the transpose of *u*. This function is similar to svd_backsubstitute(), but does not multiply by *b*. It returns the inverse matrix instead of a solution given by the inverse times *b*.

Parameters:

- u* left singular vectors
- w* array of singular values
- v* right singular vectors, transposed
- n* number of rows in *v*
- m* number of rows in *u*
- S_inv* Pseudo-inverse of *A*

5.9.2.5 int compute_svd (double ** a, int m, int n, double w[], double ** v)

Computes the singular value decomposition (SVD) of a matrix, $A = U\Sigma V^H$, where *U* and *V* are matrices with orthogonal columns, and Σ is a diagonal matrix holding the singular values, σ_i , associated with the singular vectors.

The most common use for an SVD is to compute a pseudo-inverse of the matrix *A*, in order to solve the linear system $Ax = b$. Once the SVD has been computed, the solution can be formed via

$$x = V\Sigma^{-1}U^T b$$

This can be performed computationally using the function svd_backsubstitute().

In the case of small singular values, e.g. $0 < \sigma_i < 1$, computing the inverse of Σ will induce excessively large contributions from the associated singular vectors. Thus, it is common to specify a threshold—discarding singular values and associated vectors

below the threshold to limit such effects. To perform this in C programs, one needs to set all singular values below the threshold to zero.

Note, this function accepts only real-valued input. To find the SVD of a complex-valued matrix, one can split the real and imaginary components as

$$Ax = (\operatorname{re}\{A\} + j\operatorname{im}\{A\})x = b$$

$$\begin{bmatrix} \operatorname{re}\{A\} & -\operatorname{im}\{A\} \\ \operatorname{im}\{A\} & \operatorname{re}\{A\} \end{bmatrix} \begin{bmatrix} \operatorname{re}\{x\} \\ \operatorname{im}\{x\} \end{bmatrix} = \begin{bmatrix} \operatorname{re}\{b\} \\ \operatorname{im}\{b\} \end{bmatrix}$$

Usage:

```
double **A;
double **U;
double *W;
double **V;
double **A_inv;

A = alloc2double(m,n);
V = alloc2double(n,n);
W = alloc1double(n);
A_inv = alloc2double(n,m);

compute_svd( A, m, n, W, V );
U = A;
compute_pinv( U, W, V, n, m, A_inv);

free2double(A);
free2double(V);
free1double(W);
free2double(A_inv);
```

Credits: from CWP/SU. Similar to code in Netlib's EISPACK and CLAPACK. See also discussions in NR in C

Parameters:

- a*** input matrix to decompose, will be overwritten by the left singular vectors
- m*** number of rows in ***a***
- n*** number of columns in ***a***
- w*** an array of output singular values
- v*** a matrix output of the right singular vectors, transposed

5.9.2.6 void free1double (double * p)

free memory allocated by alloc1double().

5.9.2.7 void free2double (double ** p)

free memory allocated by alloc2double().

5.9.2.8 int lsv (COMPLEX * A, int m, int n, COMPLEX * x0, double * sigma, COMPLEX * v, float thresh)

Estimate of the dominant Left Singular Vector

The function employs an iterative algorithm that solves

$$\max_x \|A^H x\|$$

to estimate the left singular vector associated with the largest singular value. (from this vector, the singular value and associated right singular vector can also be determined.)

If A is tall-and-thin, i.e. the number of rows, m, is much larger than the number of columns, n, then this algorithm is significantly faster than computing the SVD directly.

The function is most useful when only a rank-one estimate of the matrix is desired.

Parameters:

A the input matrix.

m number of rows in input matrix.

n number of columns in input matrix. Note, it is assumed that $m \gg n$

x0 the output vector. size: m x 1 (needs to be pre-allocated)

thresh [opt] convergent threshold (default=1e-4)

5.9.2.9 int rank_one_est (COMPLEX * C, float * mask, int Nx, int Ny, double * d, COMPLEX * u, COMPLEX * v, int tid)

uses Lanczos algorithm to determine singular vectors associated with the largest singular value.

Parameters:

C input data

Nx number of rows in input data

Ny number of columns in input data

d the largest singular value. (Set to NULL if undesired)

- u* the right singular vector associated with the largest singular value. (Set to NULL if undesired)
- v* the left singular vector associated with the largest singular value. (Set to NULL if undesired)
- tid* thread id for the Lanczos algorithm code. Set to zero is not using threads.

5.9.2.10 void svd_backsubstitute (double ** *u*, double *w*[], double ** *v*, int *n*, int *m*, double *b*[], double *x*[])

Perform back substitution of the singular value decomposition, operation on the objective, *b*, to compute the solution, *x*, of the linear system of equations.

Back-substitution can be performed much more quickly than explicitly computing the pseudo-inverse. However, if the inverse will be used to operate on multiple data sets (as in UNFOLD-SENSE), it is preferable to compute the inverse once and then apply it to all time frames in the series.

Credits: from CWP/SU. Similar to code in Netlib's EISPACK and CLAPACK. See also discussions in Numerical Recipes in C.

Parameters:

- u* Left singular vectors
- w* Array of singular values
- v* right singular vectors
- n* number of rows in *u*
- m* number of columns in *v*
- b* objective
- x* output

5.9.2.11 void svd_sort (double ** *u*, double * *w*, double ** *v*, int *m*, int *n*)

Sort the singular values and corresponding singular vectors in descending order

Assumes the input of the singular value decomposition of a matrix $a[][]$ of the form: $a[][] = u[][] w[] v^t [[]]$

Credits: Nils Maercklin, GeoForschungsZentrum (GFZ) Potsdam, Germany, 2001.

Parameters:

- u* left singular vectors
- w* array of singular values
- v* right singular vectors, transposed

5.10 Parallel Imaging Algorithms

Image reconstruction methods for subsampled data acquired using multiple receiver coils.

Functions

- `int apply_vbc_coefs (DATA_OBJ *input, DATA_OBJ *output, DATA_OBJ *vbc_obj)`
- `int compute_root_sum_of_squares (DATA_OBJ *input, DATA_OBJ *output, double *max)`
- `int compute_virtual_body_coil (DATA_OBJ *input, DATA_OBJ *output, DATA_OBJ *vbc_obj)`
- `int export_grappa_coef (GRAPPA_PARMS **gparm, DATA_OBJ *gexport, int ncoil, int nslc)`
- `void generate_b1_filter (int fill_fac, short Ny, short Nz_proc, float *samp_dens, float *filt_b1)`
- `int grappa (COMPLEX *I, int *PhaseLines, dataheader *hdr, COMPLEX *O, int *Nlines, int **OutPhaseLines, int YKS, int XKS, float radius, int ndk, int *dks_in)`
- `int grappa_calc_parms (dataheader *hdr, COMPLEX *O, int YKS, int *indx0, int XKS, int *indx3, int naacs, int *acsl, int kxnum, COMPLEX **gparm, int fullsq, int direction)`
- `int grappa_calc_recon_coef (COMPLEX *O, int *PhaseLines, dataheader *hdr, GRAPPA_PARMS *gparm, float radius)`
- `int grappa_for_cine (short Nx, short N_acq, short Ny, int Ny_proc, short Nz_proc, short Nf, short ncoils, short fill_fac, short fr1, int first_line, float pF, KCOORD *kline_c, float *samp_dens, float *weight_pF, COMPLEX *buf2, COMPLEX *b1, COMPLEX *data, COMPLEX *full)`
- `int grappa_recon (dataheader *hdr, COMPLEX *O, int YKS, int *indx0, int XKS, int *indx3, int *bins, COMPLEX *gparm, float radius)`
- `int grappa_recon_all_slices (DATA_OBJ *data_frame, int *phase_list, int *nphz, GRAPPA_PARMS **gparm_all)`
- `int grog_generate_eigd (GRAPPA_PARMS **gparm, int ncoil, int nslc)`
- `int grog_grid_2Ddata (DATA_OBJ *smpl_x, DATA_OBJ *smpl_y, DATA_OBJ *kdata, DATA_OBJ *src, DATA_OBJ *new_x, DATA_OBJ *new_y, DATA_OBJ *kdata_out, GRAPPA_PARMS *gparms)`
- `int import_grappa_coef (GRAPPA_PARMS ***gparm_out, DATA_OBJ *gimport)`
- `int inv_sens_matrix (short ncoils, short npts, float thresh, double **a, double *w, double **v, double *wgt_roe, double *wgt, double **S, double **S_buf, double **S_inv, double **S_inv_buf)`
- `int rlsgrappa (COMPLEX *I, int *PhaseLines, dataheader *hdr, COMPLEX *O, int *Nlines, int **OutPhaseLines, int YKS, float radius, int ndk, int *dks_in, float lambda)`

- void self_ref_b1_basic (COMPLEX *kspace_data, float b1snr_thr, short Ny, short Nx, short Nz, short ncoils, short Nf, fil_fft_mngr *mngr, COMPLEX *b1)
- void self_ref_b1_for_cine (COMPLEX *kspace_data, float sigmak, float b1snr_thr, short N_acq, short Nx, short Ny, short Ny_proc, short Nz_proc, short ncoils, short Nf, short fr1, short fill_fac, short first_line, float *filt_b1, KCOORD *kline_o, KCOORD *kline_e, float *samp_dens, fil_fft_mngr *mngr, COMPLEX *bufsp, COMPLEX *b1)
- int self_ref_b1_via_geyser (COMPLEX *datain, dataheader *hdr, int *PhaseLines, COMPLEX *ptrW, fil_fft_mngr *mngr, int m)
- int spacerip_for_cine (short Nx, short N_o, short N_e, short N_c, short Ny, int Ny_proc, short Nz_proc, short Nf, short ncoils, float pF, KCOORD *kline_o, KCOORD *kline_e, KCOORD *kline_c, COMPLEX *b1, COMPLEX *buf, COMPLEX *data, COMPLEX *spacerip, short recon_flag)
- int sprip3d_conv_pts2y (int nph, int *phz_y, int *phz_z, int M, int N, int *Y)
- void sprip3d_lsqr_init (int nph, int M, int N, int L)
- void sprip3d_lsqr_post ()
- void sprip3d_lsqrsovlv (int *Y, int nph, int m, int n, int L, COMPLEX *W, COMPLEX *Sk, COMPLEX **I, float *inlams, int lamsize, int maxits, double *xnormout, double *Rout, int tid)
- void sprip_cgslv (int *Y, int nph, int n, int L, COMPLEX *Wx0, COMPLEX *u, COMPLEX *x, COMPLEX lambda, int k_max, int tid)
- void sprip_cgslv_init (int nph, int N, int L, int threadnum)
- void sprip_cgslv_post ()
- void sprip_cgslv_recon (float *phz_encode_list, int P, int N, int M, int L, COMPLEX *W, COMPLEX *Sk, double tau, int maxits, COMPLEX *rho, int tmax)
- void sprip_lsqr_init (int nph, int N, int L, int threadnum, int lamsize, int maxits)
- void sprip_lsqr_post ()
- void sprip_lsqr_recon (float *phz_encode_list, int P, int N, int M, int L, COMPLEX *W, COMPLEX *Sk, float *lams, int numlams, COMPLEX *D, int maxits, COMPLEX **rho, double *xout, double *rout, int tmax, float *usedlams)
- void sprip_lsqrsovlv (int *Y, int nph, int N, int L, COMPLEX *Wx0, COMPLEX *Sk, COMPLEX **I, float *lams, int lamsize, COMPLEX *D, int maxits, double *xnormout, double *Rout, int tid, float *lout)
- void vdsense (short Nx, short N_acq, short Ny, short Ny_proc, short Nz_proc, short Nf, short ncoils, short fill_fac, short fr1, short first_line, float pF, fil_fft_mngr *mngr, KCOORD *kline_o, KCOORD *kline_e, float *samp_dens, float *weight_pF, COMPLEX *buf, DATATYPE *Uarray, COMPLEX *data, COMPLEX *vdsen_ima)
- void vdsense_apply (short Nx, short Ny, short Nz, short Nf, short ncoils, COMPLEX *sen_before, DATATYPE *Uarray, COMPLEX *sen_after)
- void vdsense_prep (short Nx, short Ny, short Nz, short ncoils, float thresh, int accel, XCOORD *alias, COMPLEX *b1, DATATYPE *Uarray)

5.10.1 Detailed Description

Image reconstruction methods for subsampled data acquired using multiple receiver coils.

Parallel imaging employs multiple receiver coils, which effectively apply a spatial-domain encoding in addition to the Fourier-domain encoding traditionally employed by MR imaging.

With multiple coils, the MR data acquisition can be modeled by the following signal equation [A]:

$$s_l(\mathbf{k}) = \int_V \rho(\mathbf{r}) W_l(\mathbf{r}) e^{-j\mathbf{k}\cdot\mathbf{r}} d\mathbf{r}$$

One approach to solve this inverse problem computationally is to first discretize the terms and then concatenate the equations for all coils to form a single linear system of equations.

$$\mathbf{s} = \mathbf{P}\rho$$

where \mathbf{P} is described by an estimate of the coil sensitivity maps and the phase-encoding pattern employed. The library provides one approach to estimating coil sensitivity maps, using self-referenced data [D].

Two methods in the NC-IGT fast imaging library employ this approach, SENSE [A] and SPACE RIP[F]. The SENSE functions provide reconstruction of uniformly subsampled data, i.e. where the distance is k-space between each phase-encode line is the same. Variable density SENSE [B] can be employed in those cases where low-frequency and high-frequency k-space are each uniformly sub-sampled, but at different rates. E.g. 2x in the low-frequency range, and 4x in the high-frequency range.

For sampling patterns with a wider variety of k-space distances, that is *non-uniform* subsampling, one can employ SPACE RIP. Two iterative linear system solvers are provided for SPACE RIP reconstructions: CG [E] and LSQR-Hybrid [I]. At high-acceleration factors, it is often useful to employ regularization.

$$\begin{bmatrix} \mathbf{s} \\ 0 \end{bmatrix} = \begin{bmatrix} \mathbf{P} \\ \lambda\mathbf{I} \end{bmatrix} \rho$$

The LSQR-Hybrid method can efficiently find all of the solutions corresponding to a number of regularization parameter values. The "best" image as measured by L-curve methods is then presented as the solution. For a single regularization parameter, CG is slightly faster than LSQR-Hybrid, so this method is provided as well.

An alternate approach to solving the inverse problem is to view the acquisition in k-space as a convolution between two spatial-domain functions. This is the approach taken by GRAPPA [G]. This method *does not* explicitly employ estimates of the coil

sensitivity maps. Rather it maps various output data points together to estimate a convolution kernel combining data from all coils.

Modelling GRAPPA as a matrix operator [L], one can modify the target distance for reconstructed points at will using an Eigen decomposition of the operator [M]. Since Ver 2.0, the library includes functions to compute GRAPPA coefficients suitable for GROG, as well as functions to apply GROG in multi-line radial acquisitions as in PROPELLER [N].

The NC-IGT GRAPPA implementation can reconstruct data acquired using non-uniform sampling patterns, although the visual results typically contain more noise than a corresponding SPACE RIP reconstruction. GRAPPA is the method of choice, however, in cases where aliasing due to a reduced-field-of-view is present in addition to aliasing resulting from subsampling.

It is noted as well that combinations of GRAPPA, VD-SENSE, and SPACE RIP, can often produce better images than any single algorithm alone.

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5.10.2 Function Documentation

5.10.2.1 `int apply_vbc_coefs (DATA_OBJ * input, DATA_OBJ * output, DATA_OBJ * vbc_obj)`

apply a set of coefficients calculated by `compute_virtual_body_coil` to a new set of input data.

If the output object is that same as the input, the input data will be overwritten, and the size adjusted accordingly

Parameters:

- input* the input coil data, sized [x-y-c] or [x-y-z-c]
- vbc_obj* returns the coil combination coefficients, if non-NULL

5.10.2.2 `int compute_root_sum_of_squares (DATA_OBJ * input, DATA_OBJ * output, double * max)`

Computes the root-sum-of-squares image from the input data.

input data can be either 3d: x-y-c, or 4d: x-y-z-c

The scaling factor needed to normalize the image (set the max pixel value to '1') is returned in 'max'

Parameters:

- input* input data

output output data (magnitude only, no phase)

max image normalization scale factor (calculated, but not applied)

5.10.2.3 `int compute_virtual_body_coil (DATA_OBJ *input, DATA_OBJ *output, DATA_OBJ *vbc_obj)`

An implementation of [J], which builds on ideas in [K] for identifying alternate subspaces for receiver coil representations. This implementation normalizes each of the coils, and finds the dominant subspace support along the coil dimension of the data. This generates a *virtual body coil*, which can be used in parallel imaging to produce image reconstructions with more homogeneous illumination in a self-referenced way.

Usage:

With SENSE or SPACE RIP, one can renormalize the sensitivity estimates before the reconstruction step:

```
self_ref_b1_via_geyser( K, hdr, PhaseLines, W, mngr, 0 );
compute_virtual_body_coil( W, hdr.Nx, hdr.Ny, hdr.ncoils, Bv );
for (cnt=0;cnt<hdr.ncoils;cnt++) {
    for (cnt2=0;cnt2<hdr.Nx*hdr.Ny;cnt2++) {
        W[ cnt*hdr.Nx*hdr.Ny + cnt2 ] =
            complex_division( W[ cnt*hdr.Nx*hdr.Ny + cnt2 ],
                             Bv[ cnt2 ] );
    }
}
```

Alternatively, after reconstructing with GRAPPA, one can find the associated virtual body coil image via the projection across all coil images. See the `grappa.c` MEX file for an example.

Note that the virtual body coil image contains phase information, so it can be used in applications where a root-sum-of-squares body coil estimate is unsuitable.

Parameters:

input the input coil data, sized [x-y-c] or [x-y-z-c]

output the output virtual body coil. If (output->data == NULL), memory will be allocated.

vbc_obj returns the coil combination coefficients, if non-NULL

5.10.2.4 `int export_grappa_coef (GRAPPA_PARAMS **gparm, DATA_OBJ *gexport, int ncoil, int nslc)`

Converts an array of grappa parameters into a DATA_OBJ suitable for output to a .nd file, using `write_nd_data2`. Each location in the array is assumed to be for a specific

slice of data, and the grappa kernel is presumed to be the same size (resulting in the same number of grappa coefficients) for each slice.

The returned data object will have the meta-data field populated, with a brief description of how the coefficients are arranged. This meta-data can be decoded in matlab using `load_gparms.m` or in C using `import_grappa_coef()`, with the data properly organized so that previously generated coefficients can be correctly used in future applications.

Parameters:

- gparm* the input array of grappa parameters, one set for each slice
- gexport* the output data object
- ncoil* the number of coils associated with the grappa parameters
- nslc* the number of slices in the input array

5.10.2.5 void generate_b1_filter (int fill_fac, short Ny, short Nz_proc, float * samp_dens, float * filt_b1)

Generate a 2D Gaussian filter to extract the ky-kz region, near k-space center, to be used for sensitivity mapping.

Parameters:

- samp_dens* Sampling density
- filt_b1* Gaussian filter to select ky-kz region to be used for B1 mapping.

5.10.2.6 int grappa (COMPLEX * I, int * PhaseLines, dataheader * hdr, COMPLEX * O, int * Nlines, int ** OutPhaseLines, int YKS, int XKS, float radius, int ndk, int * dks_in)

An implementation of “Generalized autocalibrating partially parallel acquisitions,” by M. A. Griswold, P. M. Jakob, et. al.. *Mag Reson Med*, 47(6):1202-1210. Jun 2002. [DOI]

Processing is done in k-space, coil-by-coil. The reconstructed data includes all coils. To form an image, one can use root-sum-of-squares.

[deprecated]

Parameters:

- I* input data
- PhaseLines* input phase index list
- hdr* header associated with input data

O buffer to hold output data. This should be Nvertical x xres x Ncoils, i.e. zero padded

Nlines number of non-zero output lines

OutPhaseLines list of output non-zero lines (will be malloced)

YKS grappa-kernel size, y-dim (2 or 4)

XKS grappa-kernel size, x-dim (must be odd)

radius size of reconstruction radius along freq-encode dimension. In some cases (e.g. coil sensitivity estimation) the full read-out length is not needed

ndk number of Delta k's to compute. If zero, then the dks list is computed automatically.

dks_in the list of Delta k's to compute. Set to NULL if ndk = 0.

5.10.2.7 int grappa_calc_parms (dataheader * *hdr*, COMPLEX * *O*, int *YKS*, int * *indx0*, int *XKS*, int * *indx3*, int *nacs*, int * *acsl*, int *kxnum*, COMPLEX ** *gparm*, int *fullsq*, int *direction*)

Calculate GRAPPA reconstruction parameters for the given data.

called by `grappa`

Example: for a 2x5 GRAPPA kernel, to reconstruct data sampled at 2x acceleration...
`YKS = 2; indx0 = {-1,1}; XKS = 5; indx3 = {-2,-1,0,1,2};`

Parameters:

hdr header associated with input data

O zero-padded k-space data

YKS size of kernel along phase encode direction (length of *indx0*)

indx0 phase encode offsets for kernel

XKS size of kernel along read-out direction (length of *indx3*)

indx3 sample offsets along readout

nacs number of ACS lines

acsl array of ACS line indices

kxnum number of readout (k_x) points used for calibration

gparm the output GRAPPA parameters. Pass a NULL pointer, memory for the parameters will be allocated and returned.

fullsq for GROG: set to 1 if full dx set is needed, 2 for both dx and dy data set. set to 0 otherwise

direction for GROG: modifies the yoffset value by {0 [default],+1,-1}.

5.10.2.8 int grappa_calc_recon_coef (COMPLEX * *O*, int * *PhaseLines*, data-header * *hdr*, GRAPPA_PARMS * *gparm*, float *radius*)

The primary function for calculating GRAPPA coefficients.

Input the source calibration data (ACS) and the phase lines where that data was acquired, and the parameters will be returned in 'gparm'.

Parameters:

O buffer holding zero-padded input data. This should be Nvertical x xres x Ncoils

PhaseLines input list of phase index showing which lines of *O* have data.

hdr header associated with input data

gparm need to predeclare the kernel size (gparm->YKS and gparm->XKS) and gparm->parray (set to NULL). ndk and dks may also be preset, or set to ndk=0 and dks=NULL for values computed from PhaseLines. For standard GRAPPA parameters, set hdr->grog = 0; For GROG, use hdr->grog = 1 for a square parameter set, suitable for GROG along the phase encode direction. use hdr->grog = 2 for an additional set of parameters suitable for GROG along the readout direction.

radius width, (0.0 .. 1.0], along the readout line to use in calibration

5.10.2.9 int grappa_for_cine (short *Nx*, short *N_acq*, short *Ny*, int *Ny_proc*, short *Nz_proc*, short *Nf*, short *ncoils*, short *fill_fac*, short *fr1*, int *first_line*, float *pF*, KCOORD * *kline_c*, float * *samp_dens*, float * *weight_pF*, COMPLEX * *buf2*, COMPLEX * *b1*, COMPLEX * *data*, COMPLEX * *full*)

A function to call GRAPPA from cine_unf

Parameters:

Nx Size of input dataset, along kx (readout)

N_acq k locs acquired / frame (in ky-kz plane)

Ny Size of input dataset, along ky (phase)

Ny_proc Ny used for processing, in vdsense

Nz_proc Nz used for processing

Nf number of frames (either time or phase)

ncoils Number of coils

fill_fac fill factor, to accomodate non-int samp pts

fr1 whether 1st frame considered even (0) or odd (1)

first_line First y line kept, when cropping recon FOV

pF partial-Fourier (1=fully sampled, 0.5=50% sampled)

kline_c array of acquired phase encode lines

b1 pointer to coil sensitivity map data

data pointer to input data

full pointer to reconstructed data

5.10.2.10 `int grappa_recon (dataheader * hdr, COMPLEX * O, int YKS, int * indx0, int XKS, int * indx3, int * bins, COMPLEX * gparm, float radius)`

reconstruct the missing data using GRAPPA.

called by `grappa`

Parameters:

hdr structure describing the data

O the (zero-padded) input data

YKS size of kernel along phase encode direction

indx0 phase encode offsets for kernel

XKS size of kernel along read-out direction

indx3 sample offsets along readout

bins an array describing the data along the phase encoding dimension. 0 : empty ;
1 : raw data ; 2 : ACS line

gparm pointer to the GRAPPA reconstruction parameters

radius size of reconstruction radius along freq-encode dimension

5.10.2.11 `int grappa_recon__all_slices (DATA_OBJ * data_frame, int * phase_list, int * nphz, GRAPPA_PARMS ** gparm_all)`

A GRAPPA reconstruction wrapper to reconstruct a stack of slices in a single pass.

Parameters:

data_frame The input k-space data: ndim should equal '4', sized: kx-ky-z-coil
type: double-complex ('dblcl')

phase_list List of phase encode locations

nphz number of phase encode locations

gparm_all An initialized memory buffer object

5.10.2.12 `int grog_generate_eigd (GRAPPA_PARMS ** gparm, int ncoil, int nslc)`

Derives the eigen-vectors and eigen-values needed by GROG from the input GRAPPA parameters.

These are stored in the `.eig_d` and `.eig_v` pointers of the `GRAPPA_OBJ`, over-writing whatever may have been there previously.

Parameters:

- gparm* input array of GRAPPA parameters, suitable for GROG (set `gparm->grog = 1` or `2` prior to generating `gparm` coefficients)
- ncoil* number of coils associated with the input array
- nslc* number of slices associated with the input array

5.10.2.13 `int grog_grid_2Ddata (DATA_OBJ * smp1_x, DATA_OBJ * smp1_y, DATA_OBJ * kdata, DATA_OBJ * src, DATA_OBJ * new_x, DATA_OBJ * new_y, DATA_OBJ * kdata_out, GRAPPA_PARMS * gparms)`

A function to shift k-space data locations, using GROG.

the input data is a triplet array, [`smp1_x`, `smp1_y`, `kdata`] that is transformed to [`new_x`, `new_y`, `kdata_out`]. The first 5 elements are specified, while the 6th is computed.

Parameters:

- smp1_x* a 1D (double / "dbl") array of sample point locations, along the x (horizontal) axis
- smp1_y* a 1D (double / "dbl") array of sample point locations, along the y (vertical) axis
- kdata* a 1D (complex double / "dbl") array of sampled k-space data, at each {`smp1_x`,`smp1_y`} point in the previous two arrays
- src* a 1D (short int / "intr") array of indices, indicating which `kdata` point should be used for each output target listed in {`new_x`,`new_y`}
- new_x* a 1D (double / "dbl") array of destination grid locations, along x
- new_y* a 1D (double / "dbl") array of destination grid locations, along y
- kdata_out* a 1D (complex double / "dbl") array of computed k-space data, at the points specified by {`new_x`,`new_y`}
- gparms* a pointer to the GROG parameters

5.10.2.14 `int import_grappa_coef (GRAPPA_PARMS *** gparm_out, DATA_OBJ * gimport)`

Converts a DATA_OBJECT, with an appropriately defined and consistent metadata field, into an array of grappa parameters suitable for subsequent GRAPPA reconstruction calls. Each location in the array is assumed to be for a specific slice of data, and the grappa kernel is presumed to be the same size (resulting in the same number of grappa coefficients) for each slice.

(data format for gimport needs to be 'dbl')

Parameters:

gparm_out a pointer to an (empty) array of GRAPPA parameters. This function will replace the data pointer with newly allocated memory.

gimport the input data object

5.10.2.15 int inv_sens_matrix (short ncoils, short npts, float thresh, double ** a, double * w, double ** v, double * wgt_roe, double * wgt, double ** S, double ** S_buf, double ** S_inv, double ** S_inv_buf)

Estimate the inverse of the sensitivity matrix, for each pixel.

The threshold paramter is described in Madore B. "UNFOLD-SENSE: A parallel MRI method with self-calibration and artifact suppression." *Magn Reson Med* 2004; 52(2):310–320.

At the expense of artifact content (presumed to be suppressed with UNFOLD later in the processing), a matrix with less noise (i.e. greater regularization) for the i^{th} entry will be obtained. If the npts vectors representing how each one of the overlapped points is seen by the coils were orthogonal, optimum SNR (i.e. the Roemer case) would be achieved. Since the solution obtained by matrix inversion would amplify noise beyond the threshold, fool the recon to believe these vectors are more orthogonal than they really are, so that it finds smaller weights. The vector for the i^{th} component, the one under consideration, is left unchanged, while the npts-1 others are made more orthogonal to it. Each one of these npts-1 vectors has a component parallel, and one orthogonal to the i^{th} (unit) vector $uv[]$. Vectors are made more orthogonal to $uv[]$ by keeping only a fraction of the parallel component (and leaving the orthogonal one untouched). The goal of the iterative process is to find the right value that brings noise amplification down to a factor of thresh.

The implication is that the reconstructed image will have less noise than a standard psuedo-inverse, at the expense of greater artifact. It is assumed that these artifacts will then be eliminated using UNFOLD.

If UNFOLD is not being used, then one can use a very large value for thresh to suppress these iterations.

Parameters:

ncoils Number of receiver coils.

npts Number of non-degenerate points ($npts \leq n_s$, the acceleration seen by SENSE).

thresh Noise threshold.

a Matrix to invert for the SENSE recon of *npts* pixels. (of size $2 * ncoils \times 2 * accel$)

w Singular values, in the SENSE recon. (of size $2 * accel$)

v Required for backsubstitution, in the SENSE recon. (of size $(2 * accel)$)

wgt_roe Weights as in Roemer et al.

wgt Weights with present method.

S Sensitivity matrix, copy of "a".

S_buf Modified version of *S*.

S_inv Inverse of the sensitivity matrix. ($2 * accel \times 2 * ncoils$)

S_inv_buf Unfinished version of *S_inv*.

5.10.2.16 `int rlsgrappa (COMPLEX * I, int * PhaseLines, dataheader * hdr, COMPLEX * O, int * Nlines, int ** OutPhaseLines, int YKS, float radius, int ndk, int * dks_in, float lambda)`

An implementation of "RLS-GRAPPA: Reconstructing parallel MRI data with adaptive filters," by W S Hoge, F Gallego, Z Xiao, and D H Brooks, to appear in *Proc 2008 IEEE Intl Symp on Biomedical Imaging*, May 2008.

Processing is done in hybrid-space, ky-x, coil-by-coil with GRAPPA reconstruction coefficients calculated simultaneously with missing data reconstruction using an adaptive RLS filter. Currently only 'RLS-along-x' is supported.

Parameters:

I input data

PhaseLines input phase index list

hdr header associated with input data

O buffer to hold output data. This should be $Nvertical \times xres \times Ncoils$, i.e. zero padded

Nlines number of non-zero output lines

OutPhaseLines list of output non-zero lines (will be malloced)

YKS grappa-kernel size, y-dim (2 or 4)

radius size of reconstruction radius along freq-encode dimension. In some cases (e.g. coil sensitivity estimation) the full read-out length is not needed

ndk number of Delta k's to compute. If zero, then the *dks* list is computed automatically.

dks_in the list of Delta k's to compute. Set to NULL if *ndk* = 0.

lambda the rls forgetting factor

5.10.2.17 void self_ref_b1_basic (COMPLEX * *kspace_data*, float *b1snr_thr*, short *Ny*, short *Nx*, short *Nz*, short *ncoils*, short *Nf*, fil_fft_mgr * *mngr*, COMPLEX * *b1*)

Calculate B1 sensitivity maps from raw kspace data.

This is a very basic function: it applies only a 1/2 sinusoidal filter only along ky; assumes kspace is fully sampled with the DC coordinate in the center of k-space. An fftshift is during processing to ensure that the estimated coil sensitivities have smooth phase.

Parameters:

kspace_data kspace data of size (ky, kx, z, coils, t).

b1snr_thr SNR threshold for sensitivity maps.

Ny Dimension along the y/ky direction.

Nx Dimension along the x/kx direction.

Nz Dimension along the z/kz direction.

ncoils Number of coil elements in array.

Nf Number of frames in kspace_data.

mngr FFT manager

b1 B1 sensitivity maps. Size: nx-ny-nz-ncoils

5.10.2.18 void self_ref_b1_for_cine (COMPLEX * *kspace_data*, float *sigmak*, float *b1snr_thr*, short *N_acq*, short *Nx*, short *Ny*, short *Ny_proc*, short *Nz_proc*, short *ncoils*, short *Nf*, short *fr1*, short *fill_fac*, short *first_line*, float * *filt_b1*, KCOORD * *kline_o*, KCOORD * *kline_e*, float * *samp_dens*, fil_fft_mgr * *mngr*, COMPLEX * *bufsp*, COMPLEX * *b1*)

Calculate B1 sensitivity maps from the dynamic data itself (i.e. self-referenced). It uses a combination of the strategies as part of GRAPPA (k-space center sampled more densely) and TSENSE (UNFOLD-based approach).

Parameters:

kspace_data Re-ordered data of size (Nx, N_acq, Nz, nph, ncoils).

sigmak Noise level in kspace_data, as determined by eval_knoise_cine.

b1snr_thr SNR threshold for sensitivity maps.

N_acq Number of sampled lines per frame.

Nx Dimension along the x/kx direction.

Ny Dimension along the y/ky direction.

Ny_proc > Ny if sampling density > 1 at ky=0.

Nz_proc Dimension along the z/kz direction.

ncoils Number of coil elements in array.
Nf Number of frames in *k*space_data.
fr1 1st frame considered even (0) or odd (1)
fill_fac Factor to make *ky* lines integer.
first_line First line for cropping (0 = off).
flt_b1 Filter to select *ky-kz* region for B1 sensitivity mapping.
kline_o Sampling function, odd frames.
kline_e Sampling function, even frames.
samp_dens Sampling density, in *ky-kz* plane.
mngr FFT manager
bufsp Memory space, to work in.
b1 calculated B1 sensitivity maps.

5.10.2.19 int self_ref_b1_via_geyser (COMPLEX * *datain*, dataheader * *hdr*, int * *PhaseLines*, COMPLEX * *ptrW*, fil_fft_mngr * *mngr*, int *m*)

Compute the coil sensitivity estimate for one frame of data, using GRAPPA as an intermediary to fill in any gaps (of $2\Delta k$) in the low-frequency coordinate range of the acquired *k*-space data.

For reference, see Hoge WS and Brooks DH, "Using GRAPPA to improve auto-calibrated coil sensitivity estimation for the SENSE family of parallel imaging reconstruction algorithms," *Magn. Reson. Med.*, Magn Reson Med, 2008; 60(2):462-467.

Parameters:

datain input *k*-space data (size: P-N-L)
hdr a header to describe the data and associated output matrix size
PhaseLines a list of acquired phase encode indices, of length P
ptrW A buffer to store output coil sensitivity maps. (size: M-N-L)
mngr a pointer to an FFT manager
m binary flag: use a mask? default: 0

5.10.2.20 int spacerip_for_cine (short *Nx*, short *N_o*, short *N_e*, short *N_c*, short *Ny*, int *Ny_proc*, short *Nz_proc*, short *Nf*, short *ncoils*, float *pF*, KCOORD * *kline_o*, KCOORD * *kline_e*, KCOORD * *kline_c*, COMPLEX * *b1*, COMPLEX * *buf*, COMPLEX * *data*, COMPLEX * *spacerip*, short *recon_flag*)

An implementation of "Sensitivity profiles from an array of coils for encoding and reconstruction in parallel (SPACE RIP)." W. E. Kyriakos, et. al. *Magn Reson Med.* 44(2):301-308, August 2000.

SPACE RIP can be used to reconstruct data sampled non-uniformly on a rectilinear sampling grid.

Parameters:

Nx Size of input dataset, along kx (readout)
N_o k locs acquired in odd ky-kz frames
N_e k locs acquired in even ky-kz frames
N_c k locs acquired in combined frames
Ny Full matrix size along ky (phase)
Ny_proc Ny used for processing, in vdsense
Nz_proc Nz used for processing
Nf number of frames (either time or phase)
ncoils Number of coils
pF partial-Fourier (1=fully sampled, 0.5=50% sampled)
kline_o lines acquired on 'odd' frames
kline_e lines acquired on 'even' frames
kline_c lines acquired on combined frames
b1 pointer to sensitivity map data
buf pointer to available memory block
data pointer to input data
spacerip pointer to reconstructed data
recon_flag 0 for low t freqs, 1 for high t freqs

5.10.2.21 int sprip3d_conv_pts2y (int *nph*, int * *phz_y*, int * *phz_z*, int *M*, int *N*, int * *Y*)

calculate the array index values for the specified acquired phase encode points. i.e. maps (phz_y,phz_z) = (2,1) of a (MxN =) 10 x 8 image to y = 12

$y[i] = phz_z[i] * M + phz_y[i]$

```

    01234567
0 .....
1 .....
2 .x.....
3 .....
```

```

4 .....
5 .....
6 .....
7 .....
8 .....
9 .....

```

Note: the C convention (which is followed here) is to start counting at zero, which differs from Matlab, which starts counting vector elements at one.

Parameters:

nph number of acquired phase encode points
phz_y y locs of each phase encode point
phz_z z locs of each phase encode point
M total span of the FOV, along y
N total span of the FOV, along z
Y calculated list of array index values

5.10.2.22 void sprip3d_lsqr_init (int *nph*, int *M*, int *N*, int *L*)

setup the memory allocation and FFT configuration for the LSQR reconstruction algorithm of 3D imaging data, sprip3d_lsqrsvl().

Parameters:

nph number of acquired phase encode lines
M total span of the phase-encode dimension
N total span of the phase-encode dimension
L number of coils

5.10.2.23 void sprip3d_lsqr_post ()

tear-down the memory allocation and FFT configuration used during the LSQR reconstructions of 3D data.

5.10.2.24 void sprip3d_lsqrsvl (int * *Y*, int *nph*, int *m*, int *n*, int *L*, COMPLEX * *W*, COMPLEX * *Sk*, COMPLEX ** *I*, float * *inlams*, int *lamsize*, int *maxits*, double * *xnormout*, double * *Rout*, int *tid*)

Solves the inverse problem associated with one slice of the 3D SPACE RIP reconstruction algorithm, utilizing fast matrix vector products available via FFT operations *and* embedded Krylov techniques to quickly find solutions associated with multiple regularization values.

Parameters:

Y phase encode index list
nph number of phase encodes
m size of full phase encode span along y
n size of full phase encode span along z
L number of coils
W (M,N,L) coil sensitivity data
Sk (nph,L) acquired data
I pointer to reconstructed image data. If this value points to an existing memory block, a single image is returned, corresponding to the highest regularization parameter value with no aliasing in the image. If a NULL pointer is passed, then all reconstructions (one for each lambda) is returned. After copying the most desirable image, free the buffer to prevent memory leaks.
inlams list of lambda's
lamsize number of lambda's in the lams list
maxits max number of iterations
xnormout returns the norm of solution, for each lambda
Rout returns the norm of residual error, for each lambda
tid unused

5.10.2.25 void `srip_cgslv` (int * *Y*, int *nph*, int *n*, int *L*, COMPLEX * *Wx0*, COMPLEX * *u*, COMPLEX * *x*, COMPLEX *lambda*, int *k_max*, int *tid*)

Solves the inverse problem associated with one column of the SPACE RIP reconstruction algorithm, utilizing fast matrix vector products available via FFT operations

Parameters:

Y phase encode index list
nph number of phase encodes
n size of full phase encode span
L number of coils
Wx0 (n,L) coil sensitivity data
u (nph,L) acquired data
x (length n) reconstructed image data
lambda DLS regularization setting
k_max max number of iterations
tid thread id

5.10.2.26 void `srrip_cgsr_init` (int *nph*, int *N*, int *L*, int *threadnum*)

Set up memory allocation blocks and FFT plans needed for `cgsolv`

Parameters:

- nph* number of acquired phase encode lines
- N* total span of the phase-encode dimension
- L* number of coils
- threadnum* number of threads to prepare for

5.10.2.27 void `srrip_cgsr_post` ()

Tear-down the allocated memory blocks and FFT manager used with `cgsolv`

5.10.2.28 void `srrip_cgsr_recon` (float **phz_encode_list*, int *P*, int *N*, int *M*, int *L*, COMPLEX * *W*, COMPLEX * *Sk*, double *tau*, int *maxits*, COMPLEX * *rho*, int *tmax*)

Reconstruct an image using the Space-RIP paradigm, solving the linear system via the method of conjugate gradients

Parameters:

- phz_encode_list* the phase encodes used (length *P* vector) range = [0, *N*-1], < with the center of k-space at *N*/2
- P* number of phase encodes used
- N* number of reconstructed samples along phase encode direction
- M* number of samples along readout direction
- L* number of coils
- W* coil sensitivity estimate in spatial domain of size (*N*,*M*,*L*)
- Sk* acquired data in k-space domain of size (*P*,*M*,*L*)
- tau* the regularization parameter
- maxits* max number of iterations
- rho* the reconstructed image (size = *M*-by-*N*)
- tmax* max number of threads to use. valid range: [0..*M*] If 0, then default number is used. set to non-zero if memory workspace is pre-allocated.

5.10.2.29 void `srrip_lsqr_init` (int *nph*, int *N*, int *L*, int *threadnum*, int *lamsize*, int *maxits*)

setup the memory allocation and FFT manager for the LSQR reconstruction algorithm, `lsqrsolv`.

Parameters:

- nph* number of acquired phase encode lines
- N* total span of the phase-encode dimension
- L* number of coils
- threadnum* number of threads to prepare for
- lamsize* maximum number of lambda's
- maxits* maximum number of iterations

5.10.2.30 void `srrip_lsqr_post` ()

tear-down the memory allocation and FFT manager used during the LSQR reconstructions.

5.10.2.31 void `srrip_lsqr_recon` (float * *phz_encode_list*, int *P*, int *N*, int *M*, int *L*, COMPLEX * *W*, COMPLEX * *Sk*, float * *lams*, int *numlams*, COMPLEX * *D*, int *maxits*, COMPLEX ** *rho*, double * *xout*, double * *rout*, int *tmax*, float * *usedlams*)

reconstruct an image using the SPACE-RIP paradigm, solving the linear system using the LSQR-Hybrid algorithm. This algorithm embeds the regularization parameter search within each iteration, efficiently producing multiple solutions for each regularization parameter (lambda) value.

Efficiently solves:

$$\min_x \{ \|Ax - b\|_2 + \lambda \|Dx\|_2 \}$$

for multiple values of λ , where D is a diagonal regularization operator matrix.

Parameters:

- phz_encode_list* the phase encodes used (length P vector) range = $[0, N-1]$, with the center of k-space at $N/2$
- P* number of phase encodes used
- N* number of reconstructed samples along phase encode direction
- M* number of samples along readout direction
- L* number of coils
- W* coil sensitivity estimate in spatial domain of size (N, M, L)

- Sk* acquired data in k-space domain of size (P, M, L, nimgs)
- lams* array of regularization parameter. values (if *lams == NULL, use the default of 10^{-4} to 10^1 on a logarithmic scale.)
- numlams* number of lambda values in the array (max=50). if zero, then default=20 is used
- D* a length N vector for varied regularization along the reconstructed dimension. Set to NULL to use the identity matrix.
- maxits* the maximum number of iterations
- rho* the reconstructed image(s). If given a pointer, then the algorithm will return one image of size M-by-N. if (*rho==NULL), it will return an image for each of the regularization values. To avoid memory leaks, clear the returned buffer after the most desirable image is copied.
- xout* returns the estimated norm of the solution for each lambda
- rou* returns the norm of residual error, for each lambda
- tmax* maximum number of threads to use
- usedlams* an array of size M, used to return the regularization value determined by the LSQR-Hybrid algorithm for each solved problem.

5.10.2.32 void sprip_lsqrslv (int * Y, int *nph*, int *N*, int *L*, COMPLEX * *Wx0*, COMPLEX * *Sk*, COMPLEX ** *I*, float * *lams*, int *lamsize*, COMPLEX * *D*, int *maxits*, double * *xnormout*, double * *Rout*, int *tid*, float * *lout*)

Solves the inverse problem associated with one column of the SPACE RIP reconstruction algorithm, utilizing fast matrix vector products available via FFT operations *and* embedded Krylov techniques to quickly find solutions associated with multiple regularization values.

Parameters:

- Y* phase encode index list
- nph* number of phase encodes
- N* size of full phase encode span
- L* number of coils
- Wx0* (N,L) coil sensitivity data
- Sk* (nph,L) acquired data
- I* reconstructed image data
- lams* list of lambda's
- lamsize* number of lambda's in the lams list
- D* a vector to use in non-I regularization. Set to NULL if not needed/desired.
- maxits* max number of iterations

xnormout returns the norm of solution, for each lambda
Rout returns the norm of residual error, for each lambda
tid thread id

5.10.2.33 void vdsense (short *Nx*, short *N_acq*, short *Ny*, short *Ny_proc*, short *Nz_proc*, short *Nf*, short *ncoils*, short *fill_fac*, short *fr1*, short *first_line*, float *pF*, fil_fft_mgr * *mngr*, KCOORD * *kline_o*, KCOORD * *kline_e*, float * *samp_dens*, float * *weight_pF*, COMPLEX * *buf*, DATATYPE * *Uarray*, COMPLEX * *data*, COMPLEX * *vsen_ima*)

The reconstruction strategy implemented by Variable density SENSE (VD-SENSE) is to apply a Cartesian SENSE reconstruction to data that is not necessarily uniformly sub-sampled. The processing proceeds in three steps.

First, the coil sensitivity estimates are used to construct reconstruction (or un-mixing or un-aliasing) operators, based on the highest acceleration factor employed in the sampling scheme. Second, the raw data is zero padded and transformed to the spatial domain. Finally, the reconstruction operators are applied to the spatial domain representation of the acquired image data, to form the un-aliased image.

Parameters:

Nx Size in x direction
N_acq number of acquired samples along y
Ny Size in y direction
Ny_proc Ny used for processing
Nz_proc Nz used for processing (number of slices)
Nf Size in time direction
ncoils number of coils
fill_fac fill factor, to accomodate non-int samp pts
fr1 whether 1st frame considered even (0) or odd (1)
first_line First y line kept, when cropping recon FOV
pF partial-Fourier (1=fully sampled, 0.5=50% sampled)
mngr a pointer to an FFT manager
Uarray Contains an inverted SENSE matrix U for each pixel, to perform the un-aliasing.

5.10.2.34 void vdsense_apply (short *Nx*, short *Ny*, short *Nz*, short *Nf*, short *ncoils*, COMPLEX * *sen_before*, DATATYPE * *Uarray*, COMPLEX * *sen_after*)

Apply variable-density SENSE.

Parameters:

Nx Size in x direction.
Ny Size in y direction.
Nz Size in z direction.
Nf Size time direction.
ncoils Number of receiver coils.
sen_before Data, before vdsense. (size: $Nx*Ny*Nz*Nf*ncoils*sizeof(COMPLEX)$)
)
Uarray Contains an inverted matrix U for each pixel, to unalias.
sen_after Data, after vdsense. (size: $Nx*Ny*Nz*Nf*sizeof(COMPLEX)$)

5.10.2.35 void vdsense_prep (short *Nx*, short *Ny*, short *Nz*, short *ncoils*, float *thresh*, int *accel*, XCOORD **alias*, COMPLEX **b1*, DATATYPE **Uarray*)

Invert sensitivity matrices, in preparation for a vdsense reconstruction.

See `inv_sens_matrix()` for a description of the *thresh* parameter.

Parameters:

Nx Size in x direction.
Ny Size in y direction.
Nz Size in z direction.
ncoils Number of receiver coils.
thresh Threshold for noise tolerance.
accel the maximum delta k in the sampling pattern
alias Description of the aliasing PSF (where aliasing comes from).
b1 B1 sensitivity maps. (size: $Nx*Ny*Nz*sizeof(COMPLEX)$)
Uarray Array where all the inverted matrices will be stored. (size: $Nx*Ny*Nz*ncoils*sizeof(COMPLEX)$)

5.11 Filtering Functions

Functions to apply spatial and temporal filters to k-space data.

Functions

- void apodization (SCAN_INFO *hdr*, int *Nx*, float **fx*, int *Ny*, float **fy*, int *Nz*, float **fz*, KCOORD **kline_o*, KCOORD **kline_e*, COMPLEX **data*)
- void apply_ramp (COMPLEX **data*, short *Nx*, short *Ny*, short *nph*, short *ncoils*, float *rampx*, float *rampy*)
- void fermi (short *N*, float *trw*, float **f*)

5.11.1 Detailed Description

Functions to apply spatial and temporal filters to k-space data.

5.11.2 Function Documentation

5.11.2.1 void apodization (SCAN_INFO *hdr*, int *Nx*, float * *fx*, int *Ny*, float * *fy*, int *Nz*, float * *fz*, KCOORD * *kline_o*, KCOORD * *kline_e*, COMPLEX * *data*)

Apply an apodization filter, to reduce ringing.

Parameters:

hdr scan information
Nx Number of points along kx.
fx Filter function along kx.
Ny Number of points along ky.
fy Filter function along ky.
Nz Number of points along kz.
fz Filter function along kz.
kline_o Sampling function, odd time frames.
kline_e Sampling function, even time frames.
data k-space matrix to filter

5.11.2.2 void apply_ramp (COMPLEX * *data*, short *Nx*, short *Ny*, short *nph*, short *ncoils*, float *rampx*, float *rampy*)

Apply a phase ramp to kspace data, to shift the image in the spatial domain.

Parameters:

data Data to apply a phase ramp to.
Nx Size in kx direction.
Ny Size in ky direction.
nph Size time direction.
ncoils Number of receiver coils.
rampx Phase increment from x pixel to next.
rampy Phase increment from y pixel to next.

5.11.2.3 void fermi (short N , float trw , float $*f$)

Generate a fermi filter.

Parameters:

N Number of points.

trw Width of transition region where the filter passes from 1% to 99%, expressed as a fraction of the full bandwidth.

5.12 Matrix-Vector Utility Functions**Functions**

- COMPLEX inner_product (COMPLEX $*a$, COMPLEX $*b$, int n)
- void matrix_transpose (COMPLEX $*A$, int m , int n)
- void matrix_vector_product (COMPLEX $*A$, COMPLEX $*b$, int m , int n , COMPLEX $*res$)
- void matrix_vector_product_threaded (COMPLEX $*A$, COMPLEX $*b$, int m , int n , COMPLEX $*res$, int numthread)

5.12.1 Detailed Description

A collection of matrix-vector utilities for use with complex-valued data structures

5.12.2 Function Documentation**5.12.2.1 COMPLEX inner_product (COMPLEX $*a$, COMPLEX $*b$, int n)**

Calculate the inner product, $\sum_{i=1}^n a_i^* b_i$, of two complex vectors

Parameters:

a pointer to first vector

b pointer to second vector

n length of the vectors

5.12.2.2 void matrix_transpose (COMPLEX $*A$, int m , int n)

Perform $A = A^T$ where (m,n) is the size of the *input* matrix

Parameters:

A pointer to input data array

m number of rows in the data

n number of columns in the data

5.12.2.3 void matrix_vector_product (COMPLEX * A, COMPLEX * b, int m, int n, COMPLEX * res)

Compute a matrix vector product, $x = Ab$, where $x_i = \sum_j A_{i,j} b_j$.

Parameters:

- A* a pointer to the complex matrix (*m* rows, *n* columns)
- b* a pointer to the complex vector (*n* entries)
- m* number of rows in *A*
- n* number of columns in *A*
- res* a pointer to the result, a complex vector, $x = Ab$, (*m* entries)

5.12.2.4 void matrix_vector_product_threaded (COMPLEX * A, COMPLEX * b, int m, int n, COMPLEX * res, int numthread)

A threaded version of matrix_vector_product

Parameters:

- A* a pointer to the complex matrix (*m* rows, *n* columns)
- b* a pointer to the complex vector (*n* entries)
- m* number of rows in *A*
- n* number of columns in *A*
- res* a pointer to the result, a complex vector, $x = A'b$, (*m* entries)
- numthread* default=16

5.13 File I/O

Functions to read and write image and data files.

Functions

- void copy_data_obj (DATA_OBJ *dest, DATA_OBJ *src)
- void display_params (SCAN_INFO hdr)
- void dump_out (char *name, int nc_out, int nf_out, int nz_out, int ny_out, int nx_out, short temp, COMPLEX *bin)
- void free_data_obj (DATA_OBJ *data_obj)
- void init_data_obj (DATA_OBJ *data)
- int read_nd_data (char *filename, char **ptr, char *fmt, int *size, int *szI)
- int read_nd_data2 (char *filename, DATA_OBJ *dat)
- int write_nd_data (char *filename, void *bin, char *fmt, int size, int *sz)
- int write_nd_data2 (char *filename, DATA_OBJ *dat)

5.13.1 Detailed Description

Functions to read and write image and data files.

The library provides a number of functions to pass data back and forth between C and Matlab.

One method is the `.nd` data format, which is a straight forward way to save real or complex multi-dimensional data. The `.nd` file format is:

- 4-byte int giving the total number of bytes in the file (filesize)
- 4-byte char string `'nddf'`, to specify the ND data format
- 4-byte int giving the number of dimensions in the array. (size)
- array of 4-byte ints, of length (size), giving number of samples in each dimension
- 4-byte char string declaring the data type. The first 3 chars declare the data type, with the last char for real or complex.

The seven possibilities are:

- (short, 16b) integers, real or complex : `'intr'` or `'intc'`
 - floats, real or complex : `'fltr'` or `'fltc'`
 - doubles, real or complex : `'dblr'` or `'dblc'`
 - (8b) character data (strings) : `'char'`
- followed by 'the data'

Version 2 allows meta-data describing the data to also be stored.

- 4-byte int describing the length of the meta-data block, in bytes [8 + `sizeof(char)*[number of metadata bytes]`],
- 4-byte char string `'meta'`,
- the meta-data.

Alternatively, one can use the `dump_out` function to write memory contents to disk. This format writes the raw binary data in one file, and then writes an associated text file describing the format of the data.

5.13.2 Function Documentation

5.13.2.1 `void copy_data_obj (DATA_OBJ *dest, DATA_OBJ *src)`

clone a copy of a data object

if *dest* is a clean object, then the memory will be allocated.

if not, (i.e. *dest* has pre-allocated data memory) the copy will proceed if (*dest*->*init* >= *src*->*init*).

5.13.2.2 void display_params (SCAN_INFO *hdr*)

Display some of the scan parameters contained in the SCAN_INFO header

5.13.2.3 void dump_out (char * *name*, int *nc_out*, int *nf_out*, int *nz_out*, int *ny_out*, int *nx_out*, short *temp*, COMPLEX * *bin*)

Write data to file, for debugging. The function output two files, one file is a binary format with the data. The second, with suffix '_dims' records the data structure (number of coils, frames, Nz, Ny, Nx, etc.). Data can be read in to Matlab using `read_dump`.

Parameters:

- name* output filename
- nc_out* number of coils
- nf_out* number of temporal frames
- nz_out* number of slices
- ny_out* size along phase-encode dimension
- nx_out* size along read-out dimension
- temp* (unused)
- bin* the data to write to disk

5.13.2.4 void free_data_obj (DATA_OBJ * *data_obj*)

release all allocated memory associated with the input data object.

- sets the *data_obj*->*type* to NULL
- frees the *data_obj*->*data*
- clears the *data_obj*->*init* value (to '0')
- frees the *data_obj*->*metadata*, if non-NULL

5.13.2.5 void init_data_obj (DATA_OBJ * *data*)

initialize the data points and array values for an empty data object

5.13.2.6 `int read_nd_data (char *filename, char **ptr, char *frmt, int *size, int *szI)`

import/read an N-D data array file (output by savend)

Usage:

```

COMPLEX *data;
char *tmpp;
int n, cnt, sz[4];
char dtype[5] = {0,0,0,0,0};

read_nd_data( "inputdata.nd", &tmpp, dtype, &n, sz );
if ( strcmp(dtype,"dbl")==0 ) {
    data = (COMPLEX *) tmpp;
}
printf("read_nd_data read an %s %d-dimensional array of size ",dtype,n);
for ( cnt=0; cnt<n; cnt++ ) { printf(" %d",sz[cnt]);} printf(".\n");

```

Returns:

Returns a 0 if read is successful, a non-zero value otherwise. Error messages are reported to STDERR.

Parameters:

- filename* Output filename.
- ptr* pointer to the data buffer to read data to.
- frmt* pointer the file format char field.
- size* pointer the returned number of dimensions in the data.
- szI* pointer to an array that holds the number of elements in dimension.

5.13.2.7 `int read_nd_data2 (char *filename, DATA_OBJ *dat)`

import/read an N-D data array file (output by savend)

Usage:

```

DATA_OBJ img;

init_data_obj( &img );
read_nd_data2( "inputdata.nd", &img );

printf("read_nd_data2 read an %s %d-dimensional array of size ",dtype,n);
for ( cnt=0; cnt<n; cnt++ ) { printf(" %d",sz[cnt]);} printf(".\n");

```

Returns:

Returns a 0 if read is successful, a non-zero value otherwise. Error messages are reported to STDERR.

This version (version 2) can read meta-data stored at the end of the file.

Parameters:

- filename* Output filename.
- dat* pointer to the data object to populate.

5.13.2.8 int write_nd_data (char *filename, void *bin, char *frmt, int size, int *sz)

write an N-D data array to disk suitable for readnd

Usage:

```
int sz[4];
COMPLEX *ImageData;

sz[0] = (int)hdr.xres;
sz[1] = (int)hdr.yres;
sz[2] = (int)hdr.CinePhases;
sz[3] = (int)hdr.Ncoils;
write_nd_data( "I.dat", ImageData, "dblc", 4, sz );
```

Returns:

Returns a 0 if read is successful, a non-zero value otherwise. Error messages are reported to STDERR.

Parameters:

- filename* input data filename
- bin* a pointer to the output data
- frmt* a format descriptor of the data type: 'char', 'intr', 'inc', 'fltr', 'flt', 'dbl', or 'dblc'.
- size* the number of dimensions spanned by the data
- sz* the number of elements in each dimension

5.13.2.9 int write_nd_data2 (char *filename, DATA_OBJ *dat)

export/write an N-D data array file (to be read by readnd) along with any associated meta-data

Usage:

```
DATA_OBJ img;

init_data_obj( &img );

// some processing, saving the data to img.data

write_nd_data2( "img_data.nd", &img );
```

This version (version 2) will append meta-data stored in the `img.metadata` field of the object

Parameters:

- filename* Output filename.
- dat* pointer to the data object to write.

5.14 EPI specific functions

Provides common corrections needed for EPI data.

Functions

- int `calc_vrgf_data_matrix` (DATA_OBJ *vrgf, int input_res, int output_res, float time_attack, float time_flat, float time_decay, float time_sample_delay, float time_sampling_window)
- int `correct_rampsamp` (DATA_OBJ *k, DATA_OBJ *vrgf, void *scratchbuf)
- int `ngc_apply_phase_shift` (DATA_OBJ *k, DATA_OBJ *ramp, fil_fft_mngr *mngr, NGC_MEM *ngc_mem)
- int `ngc_compute_phase_shift` (DATA_OBJ *ngc_even, DATA_OBJ *ngc_odd, DATA_OBJ *ramp, fil_fft_mngr *mngr, NGC_MEM *ngc_mem)
- int `ngc_mem_init` (int *sz, int nEl, NGC_MEM *ngc_mem)
- int `ngc_mem_quit` (NGC_MEM *ngc_mem)

5.14.1 Detailed Description

Provides common corrections needed for EPI data.

These functions include that ability to grid data acquired on EPI readout gradient ramps and to correct for offsets between even and odd EPI readout lines.

See also:

- EPI Ghost Elimination via Spatial and Temporal Encoding (GESTE)
- Vendor Specific Functions: GE
- Vendor Specific Functions: Siemens

5.14.2 Function Documentation

5.14.2.1 `int calc_vrgf_data_matrix (DATA_OBJ * vrgf, int input_res, int output_res, float time_attack, float time_flat, float time_decay, float time_sample_delay, float time_sampling_window)`

This function computes the matrix to regrid EPI data that is sampled on the readout gradient attack and decay slopes.

Parameters:

- vrgf* the output regridding matrix
- input_res* number of input data on readout
- output_res* number of data points on the readout line after gridding
- time_attack* the 'ramp up' time for the gradient (in msec)
- time_flat* the 'flat top' time for the gradient (in msec)
- time_decay* the 'ramp down' time for the gradient (in msec)
- time_sample_delay* the time (in msec) between the start of the readout gradient and the start of the sampling window
- time_sampling_window* length of time (in msec) the sampling window is 'on'

5.14.2.2 `int correct_rampsamp (DATA_OBJ * k, DATA_OBJ * vrgf, void * scratchbuf)`

a function to regrid EPI data sampled on gradient ramps, using the provided gridding object

Parameters:

- k* the input ramp-sampled data (of type "flt" or "dbl")
- vrgf* the ramp-sampling gridding matrix. Needs to be of type "flt", with `vrgf.sz[0] == k.sz[0]`
- scratchbuf* A pointer to some workspace memory. Needs to be as large as the (dbl) input data memory size. If NULL, the temporary scratch space will be internally allocated.

5.14.2.3 `int ngc_apply_phase_shift (DATA_OBJ * k, DATA_OBJ * ramp, fil_ffi_mgr * mng, NGC_MEM * ngc_mem)`

Applies a pre-estimated phase correction to correct the k-space shift between the odd/even lines of EPI data.

Parameters:

- k* input k-space data, of size [Nx Ny Ncoil]

ramp input phase correction data, of length [ncoil]

mngr and FIL FFT manager

ngc_mem an pre-initialized NGC object to hold the memory buffers

5.14.2.4 **int ngc_compute_phase_shift (DATA_OBJ * *ngc_even*, DATA_OBJ * *ngc_odd*, DATA_OBJ * *ramp*, fil_fft_mngr * *mngr*, NGC_MEM * *ngc_mem*)**

Computes the estimated shift (for each coil of data) based on cross-correlation between the input even and odd EPI readout lines.

Input data type can be either "dbl" or "flt".

Parameters:

ngc_even input set of even (+Gx) EPI phase reference lines. Should be 2D, with size [Nx Ncoils]

ngc_odd input set of odd (-Gx) EPI phase reference lines. Should be 2D, with size [Nx Ncoils]

ramp an object to store the output estimated phase correction for each coil. Should be a "fltr" object of length [Ncoils]. If ramp->data is set to NULL, data object will be initialized internally.

mngr an FIL FFT manager

ngc_mem an pre-initialized NGC object to hold the memory buffers

5.14.2.5 **int ngc_mem_init (int * *sz*, int *nEl*, NGC_MEM * *ngc_mem*)**

Initializes the memory structures needed for Nyquist ghost correction when using the 3-line-at-start-of-echo-train method.

Parameters:

sz a 2D int array holding the Nx and ncoil sizes of the data used to estimate the phase correction values

nEl the number of complex data value elements (Nx * Ny * ncoil) in the EPI data to be corrected

ngc_mem the NGC memory object to hold the initialized memory

5.14.2.6 **int ngc_mem_quit (NGC_MEM * *ngc_mem*)**

Free the NGC memory

5.15 Utility Functions

Functions

- void `calc_samp_dens` (KCOORD **kline_o*, KCOORD **kline_e*, short *N_acq*, short *Nz_proc*, int *fill_fac*, short *Ny*, float **samp_dens*)
- float `eval_knoise` (SCAN_INFO *hdr*, COMPLEX **kspace_data*, KCOORD **kline_o*, COMPLEX **bufspace*)
- void `extract_ksubset` (short *ncoils*, short *nf*, short *nx*, KCOORD **kline_full*, KCOORD **kline_sub*, short *nl_full*, short *nl_sub*, COMPLEX **fullmat*, COMPLEX **submat*)
- void `fil_version` ()
- int `imnum_out` (short *next_im*, short *z_anat*, short *Nf*, short *ncoils*, short *dump_b1maps*)
- void `kstretch` (short *Nx*, short *Ny*, short *Nz_proc*, short *N_acq*, short *fill_fac*, short *ifr*, short *fr1*, KCOORD **kline_o*, KCOORD **kline_e*, COMPLEX **data*, COMPLEX **data_str*)
- void `select_kcenter` (short *firsty*, short *lasty*, short *Ny*, short *firstz*, short *lastz*, short *Nz*, float **filt*)
- int `slice_number` (int *z*, int *Nsl*, int *z_first*, char **application*)
- void `weigh_kyz` (short *ncoils*, short *nf*, short *nz*, short *ny*, short *nx*, float **weight*, COMPLEX **data*)

5.15.1 Detailed Description

5.15.2 Function Documentation

5.15.2.1 void `calc_samp_dens` (KCOORD **kline_o*, KCOORD **kline_e*, short *N_acq*, short *Nz_proc*, int *fill_fac*, short *Ny*, float **samp_dens*)

Calculate the sampling density.

Parameters:

kline_o Sampling function, odd time frames.

kline_e Sampling function, even time frames.

N_acq Number of acquired lines per frame, i.e., length of *kline_o* and *_e*.

Nz_proc Size along z, in processing.

fill_fac Factor to make ky lines integer.

Ny Matrix size along y, actual dataset.

samp_dens Sampling density, size = *Nz_proc***fill_fac***Ny*.

5.15.2.2 float eval_knoise (SCAN_INFO *hdr*, COMPLEX * *kpace_data*, KCOORD * *kline_o*, COMPLEX * *bufspace*)

Evaluate the standard deviation of the noise on the k-space data. The returned value is used to set the regularization threshold in vdsense.

Get an estimate of the noise level. Look only at the corners of the kx-ky space (don't look at the central 20% part on both axes, which may contain a lot of signal). Subtract the time average to remove most of the remaining signal. Odd and even time frames are different, so use different time averages. The remaining data should be mostly noise. Find its standard deviation.

Parameters:

- hdr* Contains scan info.
- kpace_data* k-space data (size $ncoils * Nf * N_{acq} * Nx$)
- kline_o* Sampling function, odd time frames.
- bufspace* Memory space to work in. (size: $ncoils * Nf * N_{acq} * Nx$)

5.15.2.3 void extract_ksubset (short *ncoils*, short *nf*, short *nx*, KCOORD * *kline_full*, KCOORD * *kline_sub*, short *nl_full*, short *nl_sub*, COMPLEX * *fullmat*, COMPLEX * *submat*)

From a matrix with k-space lines listed in *kline_full*, generate a subset matrix featuring only the lines listed in *kline_sub*.

Parameters:

- ncoils* Number of coils.
- nf* Number of time frames.
- nx* Size along x or kx.
- kline_full* List of ky/kz for lines in fullmat
- kline_sub* List of ky/kz for lines in submat
- nl_full* Number of lines in *kline_full*.
- nl_sub* Number of lines in *kline_sub*.
- fullmat* Full matrix to subsample.
- submat* Subsampled matrix.

5.15.2.4 void fil_version ()

Output the current version and compile time of the library.

5.15.2.5 `int imnum_out (short next_im, short z_anat, short Nf, short ncoils, short dump_b1maps)`

Calculates the image number for the next image to be written out.

Returns:

```
if (dump_b1maps == 1),
    next_im+z_anat*(Nf+ncoils);
else,
    next_im+z_anat*Nf;
```

Parameters:

next_im 1st image number to use for output.
z_anat Slice number, in anatomical order.
Nf Number of time frames.
ncoils number of receiver coils.
dump_b1maps Flag to display the B1 maps.

5.15.2.6 `void kstretch (short Nx, short Ny, short Nz_proc, short N_acq, short fill_fac, short ifr, short fr1, KCOORD * kline_o, KCOORD * kline_e, COMPLEX * data, COMPLEX * data_str)`

zero-pads the k-space data set, placing sub-sampled data in the full-sized data matrix with zeros at unsampled locations.

Take the compact representation of k-space, with a list of N_{acq} lines, each one with N_x real and imaginary values, and 'stretch' it into its normal shape, a cube having N_x by $(fill_fac*N_y)$ by N_{z_proc} complex elements. (Note that due to sparse sampling and filling, $fill_fac*N_y*N_{z_proc}$ is typically much greater than N_{acq}).

Parameters:

Nx Size in kx direction.
Ny Size in ky direction.
Nz_proc Size in kz direction.
N_acq Number of acquired ky-kz lines.
fill_fac Factor by which raw data must be stretched so that all the (fractional) ky lines become integers.
ifr Time frame under consideration.
fr1 Whether 1st frame is considered even (0) or odd (1).
kline_o Sampling function, odd time frames.
kline_e Sampling function, even time frames.
data Data to uncompress.
data_str Uncompressed version of data.

5.15.2.7 void select_kcenter (short *firsty*, short *lasty*, short *Ny*, short *firstz*, short *lastz*, short *Nz*, float * *filt*)

Generate a 2D Gaussian filter to extract a central region in the ky-kz plane.

Parameters:

- firsty* 1st ky line in selected region.
- lasty* Last ky line in selected region.
- Ny* Size of filter along ky.
- firstz* 1st kz line in selected region.
- lastz* Last kz line in selected region.
- Nz* Size of filter along kz.
- filt* Calculated filter.

5.15.2.8 int slice_number (int *z*, int *Nsl*, int *z_first*, char * *application*)

Convert the order in which slices are acquired into the anatomical order in which the output should be written.

Parameters:

- z* Slice number, according to acquisition.
- Nsl* Number of slices
- application* Specific MR application under consideration.

5.15.2.9 void weigh_ky kz (short *ncoils*, short *nf*, short *nz*, short *ny*, short *nx*, float * *weight*, COMPLEX * *data*)

Apply a correction in the ky-kz plane, e.g., to correct for sampling density.

$data[kx][ky] = data[kx][ky] / weight[ky];$

Parameters:

- ncoils* Number of coils.
- nf* Number of time frames.
- nz* Size along kz.
- ny* Size along ky.
- nx* Size along x or kx.
- weight* Correction to apply in ky-kz plane.
- data* Data to be corrected.

5.16 EPI Ghost Elimination via Spatial and Temporal Encoding (GESTE)

Functions

- int geste_calibrate_all_slices (DATA_OBJ *combo, float *phase_list, GESTE_MEM *mem)
- void geste_init (GESTE_MEM *mem_obj, DATA_OBJ *data_frame)
- int geste_interleave_frames (DATA_OBJ *even_frame, DATA_OBJ *odd_frame, DATA_OBJ *combo, int mode, GESTE_MEM *mem)
- void geste_quit (GESTE_MEM *mem_obj)
- int geste_recon_all_slices (DATA_OBJ *data_frame, float *phase_list, DATA_OBJ *img, GESTE_MEM *mem, int polarity)
- int pull_readout_data (int ndim, int *sz, COMPLEX *P, int indx_in, COMPLEX *Pfull, int indx_out)
- int run_geste (DATA_OBJ *even_frame, DATA_OBJ *odd_frame, DATA_OBJ *raw_frame, float *phase_list, DATA_OBJ *img, GESTE_MEM *mem)

5.16.1 Detailed Description

This category of functions is designed to remove Nyquist ghosts from EPI images. It is a C-code implementation of the method described in [Q].

The strategy is to use temporal encoding in a series of EPI acquisitions, so that each line of k-space is acquired using readout gradients of alternating polarity over the course of the image series.

If one interleaves data from either all the positive or all the negative readouts in two frames that were acquired in this fashion, the gradient errors associated with each readout polarity will be consistent. This reduces Nyquist ghosts substantially. The authors of PLACE [R] showed that when these images are combined coherently, the Nyquist ghosting can be further reduced due to ghost cancelation. These images result in lower temporal resolution, however, due to the need for data interleaving.

In GESTE, the Nyquist-ghost-free PLACE image is used to calibrate parallel imaging reconstruction coefficients. These coefficients are then used in the original data to reconstruct two images at each time frame: one associated with negative readout polarity gradients, and one associated with the positive readout polarity gradients. When these images are combined coherently, residual pMRI artifacts will cancel, yielding images with superior ghost suppression while maintaining the original temporal resolution.

For an example on how to call the GESTE functions, consult the geste.c Matlab MEX file.

- Q. Hoge WS, Tan H, and Kraft RA, "Robust Elimination of EPI Nyquist Ghosts via Spatial and Temporal Encoding." *Magn Reson Med*, 2010; 64(6):1781-1791.
DOI

- R. "Correction for geometric distortion and N/2 ghosting in EPI by phase labeling for additional coordinate encoding (PLACE)." Qing-San Xiang and Frank Q. Ye. *Magn Reson Med*, 57(4):731-741, 2007. DOI

5.16.2 Function Documentation

5.16.2.1 `int geste_calibrate__all_slices (DATA_OBJ * combo, float * phase_list, GESTE_MEM * mem)`

Using data combined from two interleaved frames, calculate the GRAPPA reconstruction parameters for all slices.

Parameters:

- combo* the calibration data frame. 4D, size: kx-ky-z-coil
- phase_list* (unused) a list of the sampled phase encode lines.
- mem* an initialized GESTE object of scratch memory buffers

5.16.2.2 `void geste_init (GESTE_MEM * mem_obj, DATA_OBJ * data_frame)`

Initialize the memory buffers required by GESTE. For the *data_frame*, only the size of the supported data needs to be declared prior to calling the init function.

Parameters:

- mem_obj* GESTE object of sratch memory buffers
- data_frame* a pointer to a 4D data object (sized kx-ky-slices-coil) to be processed by GESTE (for image size information)

5.16.2.3 `int geste_interleave_frames (DATA_OBJ * even_frame, DATA_OBJ * odd_frame, DATA_OBJ * combo, int mode, GESTE_MEM * mem)`

The first step of GESTE (comparable to PLACE):

- A interleave input kspace of alternating readout polarity.
- B phase align the interleaved images in the image domain,
- C and then add the two frames
- D if (*mode*==0), convert the output back in to k-space domain

Parameters:

- even_frame* frame1: even lines are positive readout k-space

odd_frame frame2: odd lines are positive readout k-space
combo combined data
mode if mode=0: revert the output data back to k-space before returning
mem an initialized memory object

5.16.2.4 void geste_quit (GESTE_MEM * mem_obj)

Clear and release the GESTE memory buffers.

An array of objects holding GRAPPA reconstruction parameters can be cleared as well. If not needed, set mem_obj->nslices to '0' and mem_obj->gparm to 'NULL'.

Parameters:

mem_obj GESTE object of scratch memory buffers

5.16.2.5 int geste_recon_all_slices (DATA_OBJ * data_frame, float * phase_list, DATA_OBJ * img, GESTE_MEM * mem, int polarity)

GESTE reconstruction of EPI data frames using previously calculated GRAPPA parameters.

Parameters:

data_frame The raw input EPI data: ndim should equal '4', sized: kx-ky-z-coil type: double-complex ('dbl')
phase_list (UNUSED). List of phase encode locations
img A preallocated data array to store the reconstructed image. sized: x-y-z-coil
mem An initialized memory buffer object
polarity declare whether first k-space line is positive (1, align to even lines) or negative (0, align to odd lines).

5.16.2.6 int pull_readout_data (int ndim, int * sz, COMPLEX * P, int indx_in, COMPLEX * Pfull, int indx_out)

This auxiliary function is used to extract all readout data of the same polarity from an EPI data set.

P, and Pfull should be the same size, with dimensions ordered as: kx-ky-z-coil

It assumes that every other line of k-space is sampled at the same polarity.

Parameters:

ndim number of dimensions in data set

sz size array, describing each dimension
P the source data
indx_in the first index of source data to read
Pfull the destination buffer
indx_out the first index for the data destination

5.16.2.7 `int run_geste (DATA_OBJ * even_frame, DATA_OBJ * odd_frame, DATA_OBJ * raw_frame, float * phase_list, DATA_OBJ * img, GESTE_MEM * mem)`

An example GESTE reconstruction function, geared towards an fMRI application. Send two raw images in, get one reconstructed image back.

Parameters:

even_frame raw input EPI data frame. Even lines have positive readout data
odd_frame raw input EPI data frame. Odd lines have positive readout data
raw_frame raw input EPI data frame, the frame to reconstruct. Could/should be equal to either *even_frame* or *odd_frame*
phase_list (UNUSED). List of phase encode locations
img reconstructed image, from *raw_frame* data
mem memory buffer object.

5.17 Image Phase Alignment Functions

Functions

- `int align_image_phase (COMPLEX *P, COMPLEX *N, int nz, int *sz, float **phzL, COMPLEX **phzC, int tmax, short int mode)`
- `int calc_phase_correlation (Phase_Correlation_Args *arg)`
- `void fit_line_to_phase (COMPLEX *v, float *mask, int N, float *ramp)`
- `int unwrap_phase (double *b, float *mask, int N)`

5.17.1 Detailed Description

This category of functions is designed to support image phase alignment, to identify and remove phase differences introduced by a shifts in kspace between two images,

This is useful in Nyquist ghost removal [O] to align data acquired on positive and negative readout gradients in EPI imaging, and in rigid image registration [P].

- O. Hoge WS, Tan H, and Kraft RA, "A method to remove Nyquist ghosts from echo planar imaging (EPI) using UNFOLD." in *Proc ISMRM 17th Scientific Meeting*, pg 571, 2009.
- P. Hoge WS, "A subspace identification extension to the phase correlation method," *IEEE Trans. Medical Imaging*, 22(2):277-280, Feb. 2003.

5.17.2 Function Documentation

5.17.2.1 `int align_image_phase (COMPLEX * P, COMPLEX * N, int nz, int * sz, float ** phzL, COMPLEX ** phzC, int tmax, short int mode)`

Align the phase of two input images. This function will modify P and N so that when added coherently, the addition is constructive.

All dimensions beyond the first two will be corrected.

Parameters:

- P* image associated with pos readout data
- N* image associated with neg readout data
- nz* number of input image dimensions
- sz* array of sizes for each dimension. Note, P and N need to be identical in size
- phzL* UNUSED
- phzC* UNUSED
- tmax* maximum number of threads
- mode* if mode=0, the phase shift is split equally to both P and N. if mode=1, the phase shift is applied only to N

5.17.2.2 `int calc_phase_correlation (Phase_Correlation_Args * arg)`

Calculates the phase correlation (normalized cross correlation) between two input matrices

$$C = \text{conj}(A) * B ./ \text{abs}(A * \text{conj}(A))$$

So that the function is threadable, the input must be a pointer to the structure:

```
typedef struct{
    COMPLEX *A;           // input 1
    COMPLEX *B;           // input 2
    int Nx;               // number of rows in A,B
    int Ny;               // number of cols in A,B
    COMPLEX *C;           // output
    short int mode;       // 0: split phase correction between A,B; 1: apply phase
} Phase_Correlation_Args;
```

5.17.2.3 void fit_line_to_phase (COMPLEX * *v*, float * *mask*, int *N*, float * *ramp*)

Solves a simple LMS problem to find the slope of a line fit to the (presumed) unwrapped phase of the input vector.

Parameters:

- v* the input vector
- mask* a windowing vector of the same length, to provide a weighted LMS fit if needed.
- N* length of *v*
- ramp* the estimate of the line slope.

5.17.2.4 int unwrap_phase (double * *b*, float * *mask*, int *N*)

A 1D phase unwrapping algorithm.

Parameters:

- b* input vector of phase (angle) values
- mask* optional binary weighting vector
- N* length of input vectors

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