Computationally Assisted MRI and its application to Fetal Brain Studies

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Overview

1. Computational techniques in imaging:

   From Computational Photography to Computational MRI

2. Overview of Some Major Topics in Computational MRI

   • Contrast Domain Methods
   • Spatial Domain Methods

3. Fetal MRI

   Challenges of Fetal MRI

   Aspects of Computational MRI for Fetal Imaging
1. Traditional Photography makes use of [directly] spatially indexed sensing

2. Computational Photography seeks to improve/expand imaging by combining potential changes in eg:
   - Type and time of data collection (longer exposure, multiple exposure, filters, multiple sensors)
   - Focus or aperture variation

   With alternative image reconstruction techniques
Some Examples of Computationally Assisted Photography

• **Increasing Field of View:**
  Combining multiple smaller images
  Image mosaicing -> Panorama building

• **Increasing Contrast:**
  Combining multiple images with the same or different sensitivities:
  High Dynamic Range Photography

• **Increasing Resolution:**
  Using Sensor or Object Motion/Shifting
to enhance Resolution via PSF deconvolution

• **Variable/Multiple Focusing/Depth of Field**
  Light Field Imaging
1. Traditional Photography makes use of [directly] spatially indexed sensing.

2. Traditional MRI uses spatial frequency based sensing.

Dimensionality and MRI

- Can Collect Spatial Frequencies by
  1. Encoding in 2D to form a slice:
     - And collect multiple slices over time to form a volume
  2. Encoding fully 3D to form a volume

- But each spatial frequency needs time to collect..
Computational Methods in MRI

• Many Techniques from computational photography translate directly to MRI.

• However... MRI also offers many different ways to create both contrast, spatial and temporal localization of signal.

  – These have motivated the development of very different approaches to computational imaging
Computational Contrast Estimation Methods in MRI
Detour... Quantitative Photography ideas...

- MRI and photography record raw signal intensities from a scene:

- In photography the brightness and colour of an object recorded are dependent variables like lighting of the scene.

- It is possible to use lighting/sensor/filter combinations to estimate the actual colour/surface material properties of an object.

  -> Create ‘Quantitative Images’ of basic material properties
Detour… Quantitative MRI ideas…

1. In MRI contrast comes from many different measured properties (eg rate of relaxation of spins, motion of tissue, diffusion of water)

2. It can be varied by varying many parameters for an acquisition eg repetition time, echo time, flip angle etc etc…

3. In basic MRI acquisitions we record image intensities (providing weighted or relative contrast) dependent on factors such as: Excitation (magnetic field and coils generating it) Absorption of the signal (RF penetration effects) Received signal (receiver coil sensitivity, amplifier gain etc)

4. As with photography it is possible to combine acquisitions to estimate Basic material properties in quantitative form (eg spin relaxation time in 1/sec or flow in vol/sec)

5. These physical units should be consistent for a given tissue even in different scans and scanners
Computationally assisted MRI Topics (I)

- **Increasing Contrast/Noise:** Combining multiple acquisitions with the same or different parameters

[Hung AH, Liang T, Sukerkar PA, Meade TJ. High dynamic range processing for magnetic resonance imaging. *PLoS One.* 2013 Nov 8;8(11)]

**Multiple Acquisitions With varying echo time:**

*Figure 7. In vivo HDR-MRI.* A series of images were acquired with constant $T_R$ at 5632 ms and varying $T_E$ as indicated. The same four LDR images were used to generate both the $T_2$ map and the HDR-MRI image. Masking of the $T_2$ map was done by manual thresholding. In the HDR image, red and yellow outlines highlight features that were not captured in one or more of the individual LDR images. HDR-MRI captures the same features as $T_2$ mapping, but is less noisy in the low signal regions. Low signal features can be accurately depicted in HDR-MRI even when the features are only visible in a single LDR image.
Simulating one contrast from another:
To reduce total imaging time


**FLAIR (fluid attenuated inversion recovery) from T2W images:**

High resolution FLAIR contrast
From a T2 Contrast MRI
Spatial Domain Methods in Computational MRI
Computationally assisted MRI Topics (III)

- Increasing Field of View:
  Because of the size of the main magnet and receiver coils, MRI scanners have a limited field of view.

  Volume Stitching:
  Multiple Partial Scans -> Whole Body Volume Surveys


Fig. 3. Composing of 3 spine volumes. Top: initial average. Bottom: result. Gray bars indicate overlap.

Deformable Volume matching of parts
Computationally assisted MRI Topics (IV)

- Increasing Dimensionality/Motion Correction
  Stitching 2D slices to 3D Volumes


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**Map-Slice-to-Volume approach**

- a: an fMRI slice from a volume stack
- b: sagittal view of a slice
- c: initial slice position
- d: position after correction
- e: reconstructed in anatomical space

**Slice-Stack approach**

- f: fMRI volume stack
- g: sagittal view of the volume
- h: initial slice positions
- i: position after correction
- j: reconstructed in anatomical space

FIG. 3. Motion correction scheme depicting map-slice-to-volume (top row) and slice-stack (bottom row) approach by sagittal view of a brain. The far left column represents (a) an fMRI slice and (f) volume of stacked slices in an activation cycle. The next two columns show (b,c) the fMRI slice and (g,h) volume as positioned by the slice selection pulse during acquisition. Spatially corrected positions representing $5\degree$ rotation of head in sagittal plane are shown for (d) the slice and (i) volume, and the last column presents reconstructed fMRI volumes from (e) the slice and (j) volume in the anatomical reference space. In the map-slice-to-volume approach, an individual slice is repositioned into the anatomical volume space as each is subject to different motion parameters and the procedure is repeated for each slice in a time series fMRI. In the slice-stack approach, accurate relocation of slices is compromised by overlooking the time interval between slices and assuming all the slices in one activation cycle are subject to the same motion parameters.
Detour: Partial Acquisitions beyond spatial stitching

• Rather than simply acquire a spatial subset of a scene
  – (like photographic mosaicing from smaller images)

• MRI allows acquisition of a spatial frequency subset

• Potential Speedup:

Form an image by collecting only parts of k-space
Increasing [Super] Resolution: Combine Multiple Low Resolution images Using Acquisition characteristics or Patient Motion to deconvolve system PSF blur: Fill out HR k-space

Decreasing Acquisition Time via Reconstruction from Partial Acquisitions: Compressed Sensing -> Sparse MRI Acquisitions

Find a representation/data collection domain that is optimally sparse

-> Collect only the parts of the signal that are important for a scene:

Use a non-linear reconstruction which enforces sparsity

Newer Techniques aim to exploit different forms of data redundancy/sparsity:

a) Spatial
b) Temporal
c) Multi-channel (spatially localized multi-coil acquisition)

[Ye, J.C. Compressed sensing MRI: a review from signal processing perspective. *BMC biomed eng* 1, 8 (2019)]
[Fully] Quantitative: MRI Fingerprinting
Aiming to synthesize ANY contrast sensitivity...
From partial acquisition of all possible contrasts

[Pre-Acquired Dictionary of signals from different tissues]

Flip Angles
Repetition Times

Create Images of ANY MRI Tissue Property...
T1 relaxation T2 relaxation Etc..
Fetal Brain MRI
Fetal MRI vs Adult MRI

- Adults (generally) can be told to remain still during an MRI study.
- Fetuses move and (generally) respond less well to requests than adults.
  - Smaller fetuses have more space and move more.
- Typical 3D adult structural MRI scans take 2-12 min.
  - Motion artifacts occur if head motion during study.
- To acquire full 3D MR image during motion without significant artifact:
  - Whole study would have to take fraction of a second.

Adult 3D MR Imaging with varying motion artifact
A Number of 3D Fetal Studies have used MR

- However often limited to studying a fraction of cases
  - Where motion does not occur

- For realistic clinical use + research studies we need
  - data from most cases not some cases

- Clinical 2D -> true 3D imaging data
Fetal MRI for 3D image Formation

• Acquire multiple 2D slices using
  – partial k-space acquisition
  – Parallel receiver coils (SENSE)

Increase speed and freeze motion in a slice.

• Collect thick slices but in different anatomical planes
  – Provide high resolution in all 3 spatial dimensions.
Example Slice Images

• **T2W Multi Slice**
  - Single shot fast spin echo (SSFSE; 2D)
  - T2 weighted
  - TR = 4500 ms, TE = 90 ms
  - Approximately 1x1x3 mm³ voxel dimension
  - 15~30 slices in each stack

• **Anisotropic resolution with thick slices**

• **Often Acquired using Real Time Planning tools**

• **Multiple Slice stacks Acquired: Axial, Sag, Coronal**
Object Motion Correction
not Whole Image Motion Correction

• Object of Interest Moving within Surrounding Tissues during scan

• Object moving rigidly (approximately)

• Surrounding tissues/fluids Deforming/flowing

• Motion Within Slice Frozen Small % of corrupted slices

• Between Slice: Full 3D rot. + trans. significant fraction of object size (unlike eg cardiac motion)

• Motion is not repetitive

But can be continuous (inc maternal breathing, heart)
Combining fast MRI with Computer Vision: Building a volume image from component parts (slices)

\[ y = T_n x_n \]

6 rigid transformation parameters estimated for EACH SLICE….

Large set of numbers..
3D MRI during Motion:

Fast 2D Imaging

+ 2D->3D Mosaicing

Reconstruction based:

- Rousseau et al [MICCAI 2005]
- Jiang et al [TMI 2007]

Intersection based:

- Kim et al [TMI 2010]
Example Extreme Motion Recovery
Example Extreme Motion Recovery
Iterative 3D reconstruction

\[ y'_k = D_k B_k S_k M_k x + v_k , \quad k = 1, \ldots, n \]

[1400x50]nkkkkkkk ,...,1, =+= vxMSBDy

Down-sampling in-plane PSF blur Slice Motion (3D)

\[ \arg\min_x \sum_{k=1}^{N} \left| \left| D_k B_k S_k M_k x - y_k \right| \right|^2 + \lambda \left| \left| \mathbf{C} x \right| \right|^2 \]

\[ \hat{x} = \arg\min_x \sum_{k=1}^{N} \left| \left| D_k B_k S_k M_k x - y_k \right| \right|^2 + \lambda \left| \left| \mathbf{C} x \right| \right|^2 \]

Fogtmann et al, PAPI 2012, TMI 2014
Combined Volume (interpolation)

Slice Stack 1

Slice Stack 2

Slice Stack 3
Daily Brain Growth Derived from 246 Fetal Brain Scans 18-36GW
Progression of Fetal MRI brain studies

• 2007-2012
  – Motion correction of clinical radiology imaging with additional acquisitions
  – Initial smaller scale studies of (clinically) normal brain development (~20-50 scans)

• 2012-present
  – Development and Use of more quantitative Neuroscience specific: computational imaging protocols
  – More robust, fine scale and automated image reconstruction and analysis pipelines
  – Large scale (Many 100’s scans) + Longitudinal imaging studies in volunteer pregnancies
Some Recent papers using Computational Fetal MRI techniques

