Compressed Sensing MRI

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# Abstract

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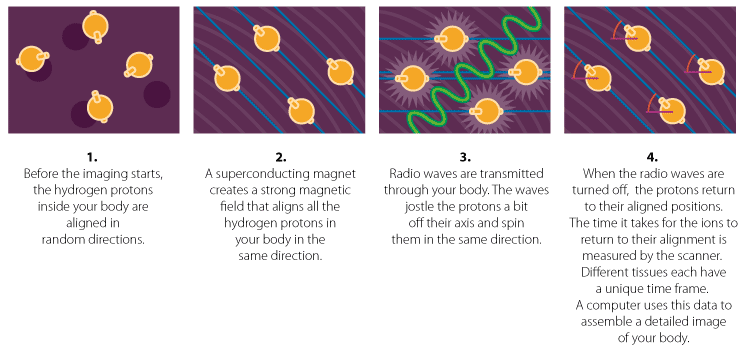
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# Introduction

2.1 Nuclear Resonance

MRI or (Magnetic Resonant Imaging) is a medical imaging technique which exploits the phenomena known as nuclear magnetic resonance. Nuclear magnetic resonance occurs due to nuclei of atoms possessing an inherent magnetic moment with an associated magnetic spin. These two quantities are dependent on the electron spin and orbital angular momentum of the atom. When a strong static magnetic field (B0)is applied, the nucleus of atoms will polarize and the magnetic moment aligns itself parallel to the static magnetic field. Applying a radio frequency (B1) of a particular frequency will disturb this orientation of magnetic moment and produce a magnetization component transverse to the static field. [1] Switching off this external radio frequency causes the nuclei to return to its externally imposed alignment and emit a detectable radio frequency. The frequency of the return RF signal is proportional to the static field strength.

In MRI, the RF signals are generated by the hydrogen molecules found in the human body. These RF signals are detected by the receiver coils of the MRI machines. A diagram indicating this process can be seen below in figure 1.



Source:<http://www.jwestdesign.com/concept/concept-3.html>

At position r, many different physical properties of tissue proportionally influence the transverse magnetization .One influencing property is proton density however other properties may be emphasized as well. MRI reconstruction aims to visualize depicting the spatial distribution of transverse magnetization.

**2.2 Spatial Encoding and K Space Trajectories**

When the RF signal (B1) is applied, the return RF signal detected by the coils in the MRI machines is the total RF signal to the region of interest where the static magnetic field is applied. For separate RF signals and hence location for protons for the whole image, the protons of the hydrogen atoms can be manipulated through the use of gradient fields. A gradient field is an additional magnetic field in addition with the strong static field(B0) to encode spatial information. By applying an additional magnetic field to a spatial position, the magnetisation of protons in the spatial position will correspond to a precessing frequency and phase. Protons on exactly in the spatial position will vary slightly in frequency depending on the strength of the magnetic field. **This can be shown in the following diagram below.** Through using at least two gradient fields, it is possible to find the location of the protons.

MRI gradient fields vary linearly in space and are signified as , and which correspond to the three Cartesian Axes. Variations in the gradient fields cause location-dependant linear phase dispersion to occur. This allows for the MRI receiver col to detect a linear phase signal dependant on the location. It can be shown that [1] that the signal equation in MRI has the form of a Fourier Integral

Where . In words this equation mean the received signal at time t is the Fourier transform of the object sampled at the spatial frequency

The MRI acquisitions method is based off the Gradient waveforms:

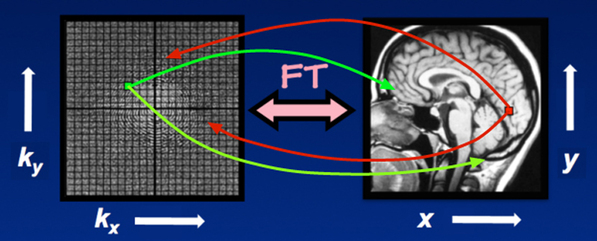
The gradient waveforms with the associated RF pulses used to produce magnetization, are called a pulse sequence [1].

**2.2 Image acquisition and K Space**

The construction of a single MR Image is found through collecting a series of frames of data, called acquisitions. In acquisitions, an RF excitation produced by magnets in the machine produces a new transverse magnetization which is them sampled along a trajectory in k-space.

The k-space is the 2D/ 3D Fourier transform of the MR image measured. It is a grid of raw data of the form ( (phase), (frequency)) obtained directly from the MR signal from MRI machine. Each point in the k space contains phase information and spatial frequency about every pixel in the final image. Conversely, each pixel in the MR image maps to every point in k-space. This concept can be seen below in figure.

This can be seen below in the image



http://mri-q.com/what-is-k-space.html

It should be noted that k-space trajectories/sampling patterns are designed to meet the Nyquist’s criterion which depends on the field of view. Under-sampling in k-space causes aliasing patterns.

Some common k-space trajectories used by MRI machines are shown below:

…

The most common trajectory used by MRIs is the Cartesian Grid using a Cartesian sampling pattern. To get the MR image from Cartesian acquisitions, the inverse Fourier transform is applied to the k-space. For non-Cartesian trajectories different reconstructions such as interpolation schemes (gridding) or back projection.

Using two gradient axes allows for spatial encoding in a 2D plane, known as a single slice of an MR image. For 3D images, multiple slices can me imaged to encode protons in a selected volume.

**Speed of MR scan**

The speed of MRI acquisition and consequently scan time of MRIs are directly correlated to the number of k-space measurements taken by the MRI scan. The speed of the MRI acquisitions by the MRI scan is limited by physical constraints such as slew-rate and maximum amplitude. For high-resolution or wide field of vision images a large number of k-space data is required to satisfy the Nyquist-Shannon criterion. This results in lengthy scan times for patients. The rapid switching and high amplitudes of the gradient fields can also produce peripheral nerve stimulation. This may make patients uncomfortable and involuntarily move. Consequently, motion during the data acquisition results in motion artefacts in the final image which results in image quality degradation.

Motion artefacts come in many forms with the most problematic being motions from cardiac motion, respiratory motion, blood flow and gross body movement. These motions usually occur within a hundred milliseconds to several seconds. These intervals are usually equal or longer than the phase encoding sampling period, hence the majority of motion artefacts come in the phase encoding direction. The most common types of motion artefacts are image blurring and ghosting (misregistration).

Image blurring occurs to random movements which produce a noisy and blurry image. Periodic or ghost images occurs due to periodic movements such as respiration, cardiac beats and arterial or Cerebrospinal fluid pulsations.

https://www.imaios.com/en/e-Courses/e-MRI/Image-quality-and-artifacts/motion

To speed up the existing methods to speed up the MR scan time include accelerating the full k-space acquisition (Echo- Planar Imaging, fast spin echo) and partial acquisition methods of k-space (CS, Parallel imaging, Partial Fourier Imaging)

Full k-space acquisition methods:

**Fast Spin Echo (FSE)**

The conventional method to obtain k-space measurements would be applying a gradient axes to apply a 90 degree pulse and 180 degree pulse. The second pulse is to refocuses spins that have been dephased due to static field homogeneities and produces an echo to be measured by the receiver coils. The time between the center of the first RF pulse and the peak of the spin echo is called the echo time (TE). The sequence repeats itself at the repetition time (TR).

Fast spin echo multiple 180 degree pulses follow each 90 degree pulse at each TR. At each 180 degree pulse a different phase-encoding gradient are is on together compared to the single phase-encoding gradient being turned on once each TR period. This allows for multiple lines in k-space (phase-encoding steps) to be collected within a given TR period. The number of echoes for each TR interval is known as the turbo factor or echo train length (ETL). The number of echoes acquired in a given TR interval is known as the echo train length (ETL) or turbo factor. Typically this ranges from 4-32 for routine imaging but may exceed 200 for rapid imaging/ echo planar techniques. http://mri-q.com/what-is-fsetse.html [source]

FSE offers advantages such as increased SNR (signal noise ratio), reduced susceptibility-induced signal losses and quicker scan times. The major disadvantages of FSE is that it may introduce Gibbs ringing artefacts and image blurring in the phase-encode directions due to the inherent T2 decay during the formation of the echo train. http://mri-q.com/what-is-fsetse.html

A recently discovered method to reduce the number of measurements samples of MRI whilst preserving image quality is to apply compressed sensing techniques to MRI.

**Echo Planar Imaging (EPI)**

EPI involves applying spin-preparation module (which could be a single RF-pulse) , a strong switched frequency-encoding gradient was applied simultaneously with an intermittently "blipped" low-magnitude phase-encoding gradient. This can be seen the diagram below. This results in a zig-zag transversal of the k-space as shown below.

This results in data from a 2D slice being able to collected following a single RF pulse. EPI can acquire slices within 50-100ms and decreases the motion artefacts due to patient motion due to its rapid imaging. A major disadvantage to EPI is its sensitive to inhomogeneity of main magnetic fields. Thus a high performance magnets are required by EPI to avoid gradient errors in imaging.

**Partial Acquisition of k-space techniques**

These methods involve taking less measurements in the k-space to speed up the scan process. The three main methods of partial acquisition include Partial Fourier Sampling, Parallel Imaging and Compressed Sensing.

**Partial Fourier Imaging**

Partial Fourier Imaging exploits inherent property of the Fourier transform known as conjugate (or Hermitian) symmetry. Conjugate symmetry applies to pairs of points (P and Q) located diagonally from each other across the k-space origin. If the data P [a + bi] is a complex, the data at Q is the complex conjugate [a - bi]. This is illustrated in the figure below. Thus in theory, only half the k-space data needs to be collected the other half can be estimated using the conjugate symmetry property. As shown below the major methods of Partial-Fourier imaging are phase-conjugate symmetry and read-conjugate symmetry.

Due to the reduction in k-space measurements, there is up to a reduction in SNR (Signal Noise Ratio) by a factor of compared to the fully-sampled sequence. Source. Furthermore, any phase errors introduced from MR imaging will make symmetrical approximations not perfect.

**Parallel Imaging**

Parallel Imaging is the acquisition of under sampled k-space data from multiple coils that receive data from the same excitation. The multiple coils have localized sensitivities and are not homogenous over the image volume. The localized sensitivities for each coil are defined in well-known arrays known sensitivities maps. When under sampled data is collected, it is done so in a predictable way which the reconstruction method chosen reconstructs a full field-of-view image without aliasing. This is done by under sampling (phase encoding lines) and sampling all (frequencies encoding lines) within these lines. The two most common are Parallel Imaging techniques are SENSE (SENSitivity Encoding) which involves acquiring separate under sampled images from each coil and combining localized sensitivities to unfold the aliased signals mathematically. and GRAPPA (GENERALIZED AUTOCALIBRATING PARTIALLY PARALLEL ACQUISITION. GRAPPA involves acquiring undersampled k space data from coils and acquiring additional data near the centre of the k-space for calibration. This additional k-space data is used to calculate GRAPPA weights and subsequently the missing k-space data before the inverse Fourier Transform.

<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4459721/figure/F9/>

<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4459721/>

This reconstruction method can be in the image domain or in the k-space domain.

[**http://www.crcnetbase.com.ezproxy.library.uq.edu.au/doi/pdfplus/10.1201/b19353-6**](http://www.crcnetbase.com.ezproxy.library.uq.edu.au/doi/pdfplus/10.1201/b19353-6)

[**http://www.crcnetbase.com.ezproxy.library.uq.edu.au/doi/pdfplus/10.1201/b19353-6**](http://www.crcnetbase.com.ezproxy.library.uq.edu.au/doi/pdfplus/10.1201/b19353-6)

**Compressed Sensing**

**The final method to speed up the MRI scan time using Partial Acquisition of k-space techniques is applying compressed sensing reconstruction process.**

**Compressed sensing fundamentals:**

**Compressed sensing involves solving the following mathematical problem:**

y = Ax

where:

A is an or sensing matrix which acquires m<<n measurements.

or the measurement matrix

or the N dimensional signal of interest we wish to reconstruct.

And where m << n and is below the Nyquist-Whitter theorem for perfect reconstruction. This mathematical can be seen below in the diagram:

This mathematical equation is an underdetermined linear system with infinite solutions. For unique reconstruction compressed sensing requires three elements must be present: sparsity, sensing matrix and recovery algorithms.

**Sparsity**

For unique reconstruction, the signal is assumed to be sparse. A signal x is k-sparse when it has at most k nonzero or mathematically:

Where , ‖∙‖0 is the 𝑙0 norm. The norms are explained in appendix 1

We let:

Denote the set of all k-sparse signals.

Typically, the signals to be reconstructed are not themselves sparse, but will be sparse in some basis Φ. In this case, x will still be referred to being k-sparse, with the understanding that we can express x as x = Φc where Many sparisfying transforms (Φ) exist such as the Discrete Wavelet transform and Cosine Transform. Both these transforms are used in widely used image formats such as MPEG and JPEG. This thesis will be using the Discrete Wavelet Transform to make the signal sparse.

The Discrete Wavelet Transform is a multiscale representation of the image. Coarse-scale wavelet coefficients represent the low resolution image component and fine-scale wavelet coefficients represent high resolution components. Each wavelet coefficient carries both spatial frequency and position information at the same time. [5] An example of the wavelet transform can be seen below.

http://statweb.stanford.edu/~markad/publications/ddek-chapter1-2011.pdf

Sensing Matrix  
The two major questions involving the design of the sensing matrix (A) is 1. How to design the sensing matrix A to ensure that it preserves the information in the signal x .2 How can we recover the original signal x from measurements y. To ensure unique reconstruction, this section will provide the desirable properties that the matrix A should have for accurate recovery.

Null-space condition

To recover all sparse signals x from y (Ax), then it is immediately clear that for any pair of distinct vectors, we must have , otherwise based of the measurements y, it will be impossible to distinguish from x. Furthermore, if then

with. Thus A uniquely represents all x if and only if the or the nullspace of A contains no vectors in . The nullspace is given as:

Many different ways exist to characterize this property, one of the most common is known as spark.

Definition 1.1 The spark of a given matrix A is the smallest number of columns of A that are linearly dependent denoted as spark (A).

Given an M x N matrix A, if spark(A) ∈ [2, m + 1], this guarantees the following:

Theorem 2.1 For any vector y ∈ , there exists at most one signal x ∈ such that y = Ax if and only if spark(A) > 2k.

When dealing with exactly sparse vectors, the spark provides a complete characterization of when sparse recovery is possible. When dealing with approximately sparse signals a somewhat more restrictive condition of the null-space.

Definition 1.2

A matrix A satisfies the null space property (NSP) of order k if there exists a constant C > 0 such that,

where Λ ⊂ {1, 2, . . . , N} is a subset of indices and = {1, 2, . . . , n}\Λ. is the length n vector obtained by setting the entries of h indexed by to zero. Similarly

To illustrate the implications of the NSP in sparse recovery, we can use the following thereom to measure the performance when dealing with general non-sparse x.

Theorem 2.2 Let represent our specific recovery method and denote a sensing matrix. If (𝑨,Δ) satisfies

Where , then A must necessarily satisfy the NSP of order 2s.

The NSP of order 2s is sufficient to establish a guarantee of the form the previous algorithm to allow for practical recovery a practical recovery algorithm for all possible. s-sparse signals.

**The restricted isometry property**

While the NSP is both sufficient and necessary for establishing of theorem …. These do not account for noise. When the measurements have been corrupted by some error such as quantization errors or noise, stronger conditions must be applied. In Cand`es and Tao[source] an isometry condition was introduced for matrix A.

Definition 2.5:

A matrix A satisfies the restricted isometry property (RIP) of order k if there exists a δk ∈ (0, 1) such that

, (1.7) for all x ∈ .

If a matrix A satisfies the RIP of order 2k, thus A approximately preserves the distance between any pair of k-sparse vectors. This also allows to maintain the stability of solutions and recover a sparse signal from noisy measurements.

To achieve RIP the minimum number of measurements/ measurement bounds are given below in the theorem.

Theorem 4

Let A be an m × n matrix that satisfies the RIP of order 2k with constant δ ∈ (0, ].

Then m ≥ Ck log ()

where C = 1/2 log(√ 24 + 1) ≈ 0.28.

We will see in Sections 1.5 and 1.6 that if a matrix A satisfies the RIP, then this is sufficient for a variety of algorithms to be able to successfully recover a sparse signal from noisy measurements.

<http://statweb.stanford.edu/~markad/publications/ddek-chapter1-2011.pdf>

As proved in source, RIP is strictly stronger than the NSP. The following theorem will prove that if a matrix satisfies RIP it also satisfies NSP.

Theorem 5: Suppose that A satisfies the RIP of order 2k with < − 1. Then A satisfies the NSP of order 2k with constant.

**Mutual coherence:**

While the spark, NSP and RIP provide guarantees for the recovery of k-sparse signals, to verify that any of these are satisfied has computational complexity, since each case must consider submatrices. It is more preferable to use properties of A that provide more concrete guarantees that are also easily computable. The mutual coherence is one such property.

Definition: The mutual coherence of a given M x N matrix A, u(A) is the largest absolute inner product between two columns ,

The lower bound is known as the Welch bound. When n>>m, the lower bound is approximately u() >= 1/sqrt(m). The mutual coherence can be related to the RIP, NSP and spark by employing the Gershgorin circle theorem.

Lemma 2.2 For any matrix A

By combining theorem … with lemma 2.2 we can pose the following contion on A that guarantees uniqueness.

Theorem: if

then for each measurement vector there exists at most one signal  such that

y = Ax.

Theorom 1.7 together with the Welch bound, provides an upper bound that guarantees uniqueness using coherence: . Another method to connect the coherence property to the RIP can be seen below.

Lemma 1.5 If A has unit-norm columns and coherence then A satisfied the RIP of order k with for all

Recovery Algorithm

**5 pages**

**Compressed sensing in MRI**

Due to the MR images being acquired in the Fourier domain and compressible, Compressed sensing is able to be applied to MRI systems. Compressed sensing is successfully achieved through three fundamental requirements: transform sparsity, incoherence of undersamplying artefacts and Non-linear reconstructions.

Transform Sparsity

A cetain signal can be recovered by applying Compressed Sensing if it is sparse in a known transform domain **Ѱ**. A signal is called nearly sparse or compressible when most of its elements are concentrated around zero. Many sparsifing transforms exist today such as the Wavelet Transform and the Discrete Cosine Transform. Such transforms are used in modern-day image video formats such as MP4 and JPEG2000. This thesis will focus on the use of the Wavelet transform to sparisfy the image data.

The Discrete Wavelet Transform is a multiscale representation of the image. Fine-scale wavelet coefficients represent high resolution image components and coarse-scale wavelet coefficients represent the low resolution image components. Each wavelet coefficient carries position information and special frequency at the same time.

Incoherent Samplying.

Due to undersamplying violating Nyquist’s theorem, uniform undersamplying exhibits coherent aliasing which may combine together and make signal recovery impossible. Applying incoherent samplying allows for strong sparse signal components to be detected and recovered through thresholding. The interference of these components are calculated and subtracted from original signal to recover the weaker sparse components.

To measure incoherence the equation in … can be used. Completely random 2D samplying can be used in theoretical calculations however is unable to practically used due to the hardware and physiological constraints. Furthermore, sampling trajectories mostly follow relatively smooth curces and lines. Howeer this does not naturally occur in random k-space samplying in all dimensions. The incoherent samplying patterns used in this thesis is the Variable Density Random undersamplying and the random phase encoding undersamplying. It should be noted that random samplying trajectories such as spiral and radial trajectories can also be used.

Variable Density Undersamplying

For images in the wavelet domain, it can be observed that coarse-scale images components tend to be less sparse than fine-scale components. Furthermore, images have a concentration of energy closer to the k-space origin.

Thus it can be concluded that for better performance with natural images, undersampling should occur less near the k-space origin and more in the peripheral of the k-space. This can be realized through choosing samples randomly with samplying density scaling according to the distance from the k-space origin. As shown in [source], using density powers of 1-6 greatly reduces the total interference and causes the iterative algorithm to produce better reconstruction and coverge faster.

Image Reconstruction

For conventional reconstruction of CS MRI images, the following constrained opstimzation problem must be solved:

Minimize:

Such that:

Where:

𝜓 is the linear operator which transforms the pixel representation into a sparse representation

𝑦 is the measured data of the MRI.

𝐹𝑢 is the under sampled Fourier transform, corresponding to a k-space undersampling scheme.

𝑚 is the reconstructed image.

ϵ is the typically the expected noise level which controls the fidelity of the reconstruction of MRI data.

The minimization of the l1 norm promotes sparsity whilst the minimization of l2 norm promotes data fidelity.

When finite-differences is used as a sparsifying transform the objective function is referred to as Total-Variation (TV), since Total variations is the sum of the absolute variations of the image. It is often useful to also include a TV penalty as well as the sparsifying transform in the objective function. This allows for the reconstructed image to be sparse in both the finite-differences and specific transform at the same time. Thus the previous equation can be written as

Minimize:

Such that:

Minimizing the l1 norm is crucial to the whole objective function. Various methods to solve equation such as homotopy, iterative soft thresholding and iteratively reweighted least squared. The conventional method (SPARSE-MRI) which solves equation… is described in appendix using non-linear conjugate gradients and backtracking line-search.

Current applications of Compressed Sensing in MRI

Due to the relatively new nature and disadvantages of Compressed sensing in MRI, it is currently not applied to many MRI scans. According to source Compressed sensing has the potential to be applied to the following areas:

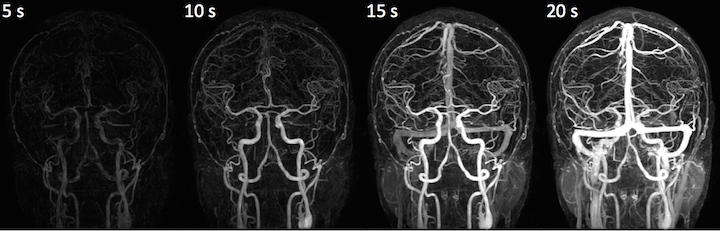
* Rapid 3D Angiography- Angiography is important for diagnosis of vascular disease. Often, a contrast agent is injected, significantly increasing the blood signal compared to the background tissue. For high temporal and spatial resolution of a large FOV, is a difficult task hence MR angiography scans are often under sampled. To reduce aliasing artefacts Compressed Sensing may be applied.
* Whole-Heart Coronary Imaging- x-ray coronary angiography is the gold standard for evaluation coronary artery disease but it is invasive. Multislice X-ray CT is a noninvasive alterative but requires high doses of ionizing radiation. MRI is emerging as a noninvasive, nonionizing alterative. Coronary arteries are constantly in motion, making high-resolution imaging a challenging task. To minimize the effects of breathing the scan can be tracking and compensating for respiratory motion. The effects of heart motion can be minimized by synchronizing acquisitions to the cardiac cycle. In current scans, the number of acquisitions is limited to the number of cardiac cycles in the breath-hold period. However with applying compressed sensing, the scan time can be decreased significantly. For example Siemens allows for a Cardiac Cine scan be done within 25 seconds free breathing compared to the conventional method of six minutes with multiple breath-holds. https://www.healthcare.siemens.com.au/magnetic-resonance-imaging/mri-technologies/speed-technologies/compressed-sensing/body-imaging
* Brain Imaging – Brain scans are the most common applications to MRI. Most brain scans use 2-D Cartesian Multislice acquisitions. The Sparsity/Compressibility of MR Images showed that brain images exhibit transform sparsity in the wavelet domain. Applying compressed sensing allows for reduction of collection time while improving the resolution of current imagery.

Current Challenges to CS MRI

Although many successful applications of Compressed sensing in MRI, conventional CS MRI has many challenged which allow it to be incapable to provide diagnostically accurate images in some imaging cases. These include:

* Design of random acquisition method of allow for incoherent undersampling- Random 2D undersampling is difficult to achieve due to the required rapid gradient switching being constrained by hardware. Furthermore the resulting artefacts and eddy currents may significantly degrade the quality of reconstructed image. A more practical method would be do apply random phase-encoding however this introduces aliasing artefacts. Other Non-Cartesian trajectories exist (e.g. radial) however are not commonly implemented in routine clinical use.
* Reduction factors of Compressed Sensing- For compressed sensing to be practically implemented Compressed Sensing must at least be greater than the reduction factor of 3 for Parallel Imaging. The reduction factor is defined as (R = , where D is the total number of points defining the grid and N is the number of samples taken). Currently implementing Compressed Sensing at higher reduction factors introduce aliasing artefacts and blur edges due to reconstruction errors. This limited the potential use of Compressed Sensing in further applications.

Existing Image processing Techniques for thesis.

In some types of MRI scans (e.g. dynamic MRI and 3D mri images) multiple images are taken of the same region of interest to produce the reconstructed image. Some of the images taken have the same information (e.g. edges, structure and physiology) can be used to reconstruct the next image taken. An example can be seen below in figure 8. As shown in the dynamic MRI scans of the brain as the contrast agent reveals the blood vessels, which are present in all the images at higher contrasts depending on time. This information may potentially be able to improve the image quality or reduce the scan time of the next image taken. An example can be seen below in figure 8. (http://mrcentre.ca/Our\_People/mlebel)

Currently many image processing techniques exist in edge detection and image registration which may be used in gathering information from a reference or previous image

Edge Detection techniques:

An edge in an image is significant local change in the image intensity, usually association with a discontinuity in the first derivative of the image intensity or the image intensity. Edges are important image features as they may correspond to significant features in the image. In MRI this is relevant as some types of MRI images are sparse (e.g. Angiography scans) and edges provide information on patient physiology. An edge detector is an algorithm that produces a set of edges from an image.

To detect edges the following steps must be applied:

1. Filtering- Since the gradient computation based on intensity values of two points are influenced by noise and other vagaries in discrete computation, an image filter is commonly applied to improve performance of edge detector.
2. Enhancement – In order to detect edges, the changes in intensity in the neighbourhood of a point must be determined. Enhancement of edges emphasizes pixels where there is a significant change in local intensity values. This is usually performed by computing the gradient magnitude.
3. Detection- Many points in an image have a non-zero value for the gradient and thus not suitable for edges in a particular application. Therefore a method should be used to determine which points are edges
4. Localization-

Image registration

CS in MRI

Existing methods half a page

**5 pages**

Image Processing: Image registration

Canny Filter

Affine Transformation

http://www.cse.usf.edu/~r1k/MachineVisionBook/MachineVision.files/MachineVision\_Chapter5.pdf

# Results

**2.1 Nuclear Magnetic Resonance**

# Conclusion

References