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Novel Compressed Sensing Algorithms with Applications to Magnetic Resonance Imaging

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Magnetic Resonance Imaging (MRI) is a widely used non-invasive clinical imaging modality. Unlike other medical imaging tools, such as X-rays or computed tomography (CT), the advantage of MRI is that it uses non-ionizing radiation. In addition, MRI can provide images with multiple contrast by using different pulse sequences and protocols. However, acquisition speed, which remains the main challenge for MRI, limits its clinical application. Clinicians have to compromise between spatial resolution, SNR, and scan time, which leads to sub-optimal performance.

The acquisition speed of MRI can be improved by collecting fewer data sam- ples. However, according to the Nyquist sampling theory, undersampling in k-space will lead to aliasing artifacts in the recovered image. The recent mathematical theory of compressed sensing has been developed to exploit the property of sparsity for signals/images. It states that if an image is sparse, it can be accurately reconstructed using a subset of the k-space data under certain conditions.

Generally, the reconstruction is formulated as an optimization problem. The sparsity of the image is enforced by using a sparsifying transform. Total variation (TV) is one of the commonly used methods, which enforces the sparsity of the image gradients and provides good image quality. However, TV introduces patchy or painting-like artifacts in the reconstructed images. We introduce novel regularization penalties involving higher degree image derivatives to overcome the practical problems associated with the classical TV scheme. Motivated by novel reinterpretations of the classical TV regularizer, we derive two families of functionals, which we term as isotropic and anisotropic higher degree total varia- tion (HDTV) penalties, respectively. The numerical comparisons of the proposed scheme with classical TV penalty, current second order methods, and wavelet algorithms demonstrate the performance improvement. Specifically, the proposed algorithms minimize the staircase and ringing artifacts that are common with TV schemes and wavelet algorithms, while better preserving the singularities.

Higher dimensional MRI is also challenging due to the above mentioned tradeoffs. We propose a three-dimensional (3D) version of HDTV (3D-HDTV) to recover 3D datasets. One of the challenges associated with the HDTV framework is the high computational complexity of the algorithm. We introduce a novel computationally efficient algorithm for HDTV regularized image recovery problems. We find that this new algorithm improves the convergence rate by a factor of ten compared to the previously used method. We demonstrate the utility of 3D-HDTV regularization in the context of compressed sensing, denoising, and deblurring of 3D MR dataset and fluorescence microscope images. We show that 3D-HDTV outperforms 3D-TV schemes in terms of the signal to noise ratio (SNR) of the reconstructed images and its ability to preserve ridge-like details in the 3D datasets.

To address speed limitations in dynamic MR imaging, which is an important scheme in multi-dimensional MRI, we combine the properties of low rank and sparsity of the dataset to introduce a novel algorithm to recover dynamic MR data sets from undersampled k-t space data. We pose the reconstruction as an optimization problem, where we minimize a linear combination of data consistency error, non-convex spectral penalty, and non-convex sparsity penalty. The problem is solved using an iterative, three step, alternating minimization scheme. Our results on brain perfusion data show a significant improvement in SNR and image quality compared to classical dynamic imaging algorithms.