Phase-sensitive Image Reconstruction

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- Phase information is extremely important in MRI.
- Many physical parameters can be measured by using phase-sensitive image reconstruction.
- MRI phase needs to be properly and carefully handled especially when it has aliasing.

MRI signal is induced by and thus proportional to the transverse component of the precessing magnetization. An MR image then represents a field of 2-dimensional vector that has both a length and a direction. The length is displayed as a magnitude image. The directional information can be described with an angle called phase, forming a phase map behind every magnitude image. Mathematically, a 2-dimentional vector corresponds to a complex number that has real and imaginary parts as those from a Fourier transform of the k-space data acquired in a receiver coil [1].

With specially designed pulse sequences, various physical quantities can be sensitized and encoded into the phase of the resulting MR images. Specific applications include phase-contrast mapping of velocity [2,3], temperature [4], magnetic field [5], susceptibility-weighting [6], and information leading to electrical current density [7] or mechanical elasticity [8]. Proper handling of phase information is also very critical in phase-sensitive inversion-recovery imaging [9], as well as Dixon water-fat imaging [10-12].

The phase value of a complex MR image is typically defined in the range of $(-\pi,\pi)$ radians for a complete cycle of rotation, and can be calculated using the four-quadrant arc-tangent function ATAN2(Im,Re) that is available in most programming languages. Very often, phase difference is computed between two similarly acquired images in order to extract the needed information from background phase errors. In such cases, it is recommended to find the arc-tangent of the product between one image and the complex conjugate of the other [1], as this operation would avoid possible artifact near $(-\pi,\pi)$ phase values when the phase difference is computed by a simple subtraction between the two individual phase maps.

It has been known for a long time that a “bi-polar gradient” can encode velocity into the phase of MR signal [2,3]. This idea can be extended to perform a “phase labeling” of position by using a “unipolar gradient”. This is the absolute physical position measured from the iso-center and thus can be used for geometric distortion correction [13,14].

If the phase sensitivity of a pulse sequence is set too high, a physical parameter such as velocity may cause a phase shift of more than $\pm\pi$ radians. Phase aliasing or “wrap” then will be seen in the resulting phase maps. It is desirable to unwrap the phase for a correct measurement of the physical parameter. However, phase unwrapping is not as easy as it appears, and remains a difficult problem involving active research in image/signal processing community [15]. A key reason for its difficulty is the existence of “poles” or “singularities”, a topological structure that is associated with a vector field. MR images with more noise and artifacts get more chances to have poles, although poles may exist in even perfectly noiseless images, making phase unwrapping difficult if not impossible without using additional information. In some cases, more straightforward phase unwrapping can be achieved along temporal dimension [16].

Certain phase-sensitive MRI techniques only uses phase as an intermediate step, the ultimate goals are something simpler. For example, the goal of phase-sensitive inversion-recovery MRI is to obtain the "polarity" in addition to magnitude for enhanced dynamic range of contrast [9]. Another example is Dixon water-fat imaging where an important step is to determine whether water or fat is more dominating in a voxel [12]. This corresponds to finding the correct polarity or spin orientation from only two possible choices at each pixel. Considering the binary nature of the polarity or spin orientation, this field is much simpler than the continuously varying phase map, without having such topological structures as poles. It is thus recommended to deal with the polarity or spin orientation field directly, rather than with the phase field, for ease of processing and improved robustness.

In most MRI applications, only magnitude images are used. However, phase information is very fundamental, if not more fundamental than magnitude, considering the fact that MR signal magnitude changes are often ultimately due to spin "de-phasing". In k-space, phase of the raw data has been demonstrated to carry more information than magnitude for visualization [17].

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