Motion Correction in MRI: K-Space Navigators

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Highlights:

- K-space navigators can be interleaved within imaging and spectroscopy sequences to obtain pose (position and rotation) information with great temporal efficiency
- Even very short k-space navigators can yield more information than just pose, such as shim and respiratory phase
- Motion and shim changes can be rapidly tracked and corrected in real time during scanning, thus reducing artifacts in the resulting images
- Complete k-space navigator solutions have been demonstrated in several sequences, including 3D spoiled gradient echo and echo-planar imaging sequences

Problem Summary:

Motion during MR acquisitions (imaging, spectroscopy) causes artifacts (ghosts, blurring, spectral line broadening) and these artifacts are especially pronounced in longer 3D-encoded scans. Navigators are short sequence elements that may be interleaved within the principal imaging or spectroscopy sequence to measure “navigational” information at frequent intervals throughout the scan. Navigational information describes the dynamic state of the subject and scanner environment, including pose (for rigid parts of the anatomy), cyclic phase (for anatomy that is affected by cardiac and respiratory phase), and field information (B0 inhomogeneity/shim). K-space navigators attempt to quantify this information rapidly by sampling the minimum required amount of data along a specially designed k-space trajectory, without creating an image. If navigational information is obtained and processed in real time, corrections to the system and sequence can be made as soon as possible during acquisition, thus reducing the artifacts that these dynamic perturbations cause in the final image or spectrum. This unit describes the history, theory and design of k-space navigators, with example implementations and applications.

Body:

K-space navigators are sequence elements that efficiently sample “navigational” information, or information related to the state of the anatomy being scanned and the magnetic environment inside the scanner. For rigid anatomy, such as that part of the head above the neck and not including the lower jaw, this includes “pose” (position and rotation). K-space navigators are well suited to obtaining efficiently the information necessary to estimate pose. To characterize non-rigid anatomical changes, more extensive image-based navigators may be more appropriate, although k-space navigators may be used to efficiently gate these changes if they are periodic (e.g. cardiac, respiratory). K-space navigators are also appropriate for efficiently estimating dynamic changes in the B0 field (“shim”), especially the scalar offset and linear spatial components. Heating of iron components (shim iron) of the scanner due to gradient activity causes a drift in the field (equivalent to “frequency drift”) while changes in the position of the subject invalidate the initial shim and result in spatially distributed B0 changes (equivalent to frequency offsets that vary across space). Respiration results in dynamically changing B0 due to the periodically changing shape of the body inside the field, even when it is outside the imaging field of view. K-space navigators can be used to efficiently estimate the spatially constant and spatially linear changes to the B0 field. Characterizing higher-order changes requires more extensive navigators. Eddy currents result in spatially varying B0 fields with short time constants and although these can be measured with k-space navigators, they are more often a nuisance to navigators designed to estimate motion and slow B0 changes.

Pose changes consist of position changes (translations) and rotations. Pose changes are therefore also called “6-degree-of-freedom” (6-dof) or “rigid body” position changes, appropriate for describing position changes of rigid organs such as the head. Center of rotation is critical – any combination of translation and rotation about a point can be equivalently described as a different translation, and rotation through the same angle about a different point. Since k-space and object space are related through the Fourier transform, it follows from the Fourier shifting theorem that translations in object space are manifest as linearly changing phase (phase “roll”) in k-space, along the same axis. Translations in object space do not affect the magnitude of the k-space representation of the object. On the other hand, rotations in object space are manifest as rotations in k-space. Therefore the effects of translations and rotations can be neatly separated in k-space and this property has been exploited in developing efficient k-space navigators.

Following from the Fourier shifting theorem, a single straight line in k-space can be used to estimate translations in object space in the direction of the line (relative to a reference). This operation can be done in k-space by complex division of each element in the two vectors of samples (navigators) followed by fitting a linear term to the phase (taking into account that the phase may wrap multiple times across the vector). The slope then corresponds to the translation. Alternatively, this operation may be performed by cross-correlating the two vectors after Fourier transformation. In object space this is equivalent to finding the shift between the projection images created from the two vectors, and it assumes a single rigid body. The venerable “pencil beam navigator” (1) works this way, although its primary application in respiratory gating requires that only a pencil-shaped column of object space, including the diaphragm, be excited, so as to eliminate any adjacent non-rigid anatomy contaminating the signal.

By collecting only the signal along a circular trajectory in k-space, rotations within the plane of the navigator (called an “orbital navigator” (2-3)) can be estimated. Relative rotations are estimated by comparing the magnitude of the features along the circle with a reference navigator, for example by simply cross-correlating the magnitude signals from the two orbital navigators. A set of three perpendicular orbital navigators can be used to estimate rotations about all three principal axes. Rotations may be out-of-plane with all three navigators, and to deal with this, the set of three navigators can be repeated after correcting for the estimated rotations, iteratively until the correct rotation is found. Alternatively, a complete map of the surface of a sphere may be obtained and the orbital navigator(s) matched to the map. In one variant, every navigator effectively describes the entire shell. This k-space navigator is called a “spherical navigator” (4) and is accompanied by sophisticated methods for rapidly computing the match to a reference navigator or map. The radius of the orbital navigator is dependent on the spatial resolution of the features of the object being tracked. A larger radius corresponds with smaller features, and theoretically better tracking accuracy, but as the radius increases, the signal-to-noise ratio (SNR) decreases, so that choosing the radius is a trade-off between accuracy and SNR.

An FID-navigator ("free induction decay") (5) is a navigator with no spatial encoding i.e. it encodes the temporal behavior of the spins at the center of k-space, or the average behavior of the spins across the entire region of sensitivity of the receive coil. The frequency component of the FID reflects the difference in frequency between the resonant frequency of these spins (dictated by the B0 field and not the transmit frequency, since any selection gradients that may have been on during transmission have been turned off) and the demodulation frequency of the RF receiver. The demodulation frequency is typically matched to the expected B0 field in a calibration procedure at the start of the scan session (along with the base transmit frequency), so that any differences reflect changes due to drift or the changes in position of the subject. Breathing alters the B0 field periodically. Frequency offsets are manifest as received signal phase that changes linearly with time after excitation. If a single straight line in k-space is used to detect translations, this estimate will be confounded by frequency offsets. However, since the phase due to frequency offsets evolves linearly and monotonically with time after excitation, whereas the linear phase due to translations varies with the applied gradients (position in k-space), these two effects can be unraveled. For example, if signal along a straight line through the center of k-space is collected twice, with opposite direction, following a single excitation, motion in the direction of the line can be distinguished from frequency drift because the phase evolves linearly with time from excitation for the frequency offset, but the phase slope due to translation changes polarity when the trajectory changes direction. The "DORK" (6) method for frequency drift estimation is based on the N/2 phase correction navigator in EPI (three central k-space lines with opposite polarity) (7) and it is robust in the presence of translations. Spatially linear B0 offsets are equivalent to small additional linear gradients and result in errors in the k-space trajectory. These are manifest as shifts in the position of the echoes (center of k-space) in readouts that traverse the center of k-space. Provided the navigator traverses the center of k-space in three directions that are not co-planar, all three linear shim corrections can be estimated in this way, and corrected by setting a constant correction current on the linear gradients.

Some of these ideas were combined in a single navigator for rigid body motion detection, called a "cloverleaf navigator" (8). This navigator includes three orthogonal straight-line sections for estimating translational components along all three principal axes, interleaved with three sections each along a quarter of an arc for estimating rotations. Since out-of-plane rotations may occur, an initial map of the region of k-space along a border region around the arcs is collected (the complete surface of a sphere is not mapped out). By reference to the map, a full 6-dof estimate of pose can be made from a single cloverleaf navigator, which takes approximately 4 ms to acquire. The navigator phase yields frequency drift, and shifts in the echoes yield linear shim information. All of these terms are corrected in real time by adjusting the gradients, RF pulse frequencies and by numerically applying phase correction to the readouts.

The initial map of k-space in the vicinity of the cloverleaf navigator is acquired by artificially adjusting the gradients for each navigator to simulate multiple example rotations. This is completed in approximately 12 s and it is assumed that the subject remains motionless during this time. It is also assumed that the effect of simulated rotations on the navigator signal is the same as the effect of real rotations. Deviations in B0 due to the motion can be measured and corrected as described above. Deviations in B1, however, are not modeled in the current system. If a rigid object moves in a phased array coil with a non-uniform B1 receive (coil sensitivity) profile, and real time motion tracking is applied, the situation may be thought of as equivalent to a stationary object with a coil moving around it. In principle these effects can be corrected if a coil sensitivity map is available. Moreover, the known spatial arrangement of the coil elements could, in principle, be exploited to accelerate the navigator or improve accuracy.

Cloverleaf navigators have been demonstrated for brain imaging in 3D spoiled gradient echo (8) and 3D EPI sequences. They (and other k-space navigator designs) can also be used, without a map, to detect whether or not a change in position or configuration of the anatomy has occurred. For example, they can be used for respiratory gating, and have been demonstrated as a method of gating during imaging of the eyeball. In these applications, it is assumed that the anatomy returns to an initial configuration at regular intervals. If this is not the case, the navigator may be used to trigger a more extensive navigator such as an image based navigator to estimate the new configuration of the anatomy.

Summary:

- K-space navigators are sequence elements that use a minimal amount of data (and therefore scan time) to obtain information about the state of the subject or scanner environment (such as head pose and B0 field changes)
- Straight line trajectories in k-space can be used to estimate translations of an object in the direction of the line, and the translation is manifest as a linear phase offset relative to the reference
- Rotations in object space correspond to rotations in k-space and can be measured in-plane with circular k-space trajectories and about any arbitrary axis with spherical k-space trajectories
- The constant and spatially linear components of B0 inhomogeneities that may arise dynamically due to respiration and changes in position can be measures using phase accumulation across the readout and shifts in the positions of the gradient echoes, respectively

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