Motion Correction in MRI: Image-Space Navigators

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Highlights:

- Image-based rigid-body motion navigators appear to acquire a significant amount of redundant information compared to strategies that rely on massively under-sampled k-space acquisitions.
- However, there are many practical arguments for acquiring this "redundant" information, particularly the ability to select and track only the relevant sub-region of the imaging FOV.
- Current work highlights the ability to use the combination of natural signal sparsity, and high-channel-count receive coils to significantly accelerate the acquisition of image-based navigators.

Problem Summary:
Acquiring complete images or volumes as motion navigators necessitates longer acquisition times than methods that massively under-sample k-space. If we assume the entire FOV contains a single object that moves rigidly, the additional information acquired in image-based methods seems redundant. In practice, though, there are significant advantages to acquiring complete images/volumes. Additionally, by taking advantage of the natural sparsity of certain contrasts and the increasing availability of high-channel-count receive coils, the time requirements of image-based navigators can be significantly reduced.

Body:
There is an inherent trade-off in using navigators to track motion during MRI scans: time during which we are acquiring the navigator is necessarily time that we cannot spend acquiring the actual data of interest. The inherent efficiency of many commonly used imaging methods (e.g., EPI and FLASH), also means that there is no "free space" in which navigators can be inserted. It therefore seems a natural constraint on practical navigators is that they be as short as possible to minimize the penalty on the sequence's efficiency. This constraint has led to a variety of methods that massively under-sample k-space and then apply the Fourier identities for rigid motion to estimate subject motion from changes at just a few points. FID navigators [1] perhaps embody the most extreme form of this strategy, using no encoding gradients and just a few points from an FID to invert a model of the interaction between coil sensitivities and rigid motion.

EPI-based acquisitions that acquire many volumes in rapid succession (e.g., fMRI and DWI) are often retrospectively motion-corrected by rigid registration. However, this can become a prospective registration-and-update loop if the processing is done in real time on the scanner. The Prospective Acquisition Correction (PACE) method [2] was developed specifically for fMRI, where each stack of slices could be registered back to the first volume and the imaging coordinates updated based on the registration output, providing a "self-navigating" sequence with no additional navigator. An extension of this method for low-b DWI has also been shown [3]. A related precursor to this is PROPELLER [4], which altered the acquisition of 2D-encoded sequences to repeatedly sample a region at the center of k-space throughout the scan. The multiple acquisitions of the same region of k-space could then be used to estimate subject motion. While in PROPELLER this registration was done in k-space using the Fourier identities for rigid motion, this can also be viewed as an implicit image registration problem. Similarly, 3D radially encoded sequences provide another form of self-navigation, where subsets of spokes can be used to reconstruct a time-series of coarse images that can be registered to estimate subject motion [5].

More recently, interest has moved to a group of sequences that fall into a third category: neither self-navigating nor extremely time constrained. Sequences in this group actually contain significant "dead time" for relaxation as part of their strategy for optimizing contrast. Prominent examples of this include the multi-echo MPRAGE (MEMPRAGE) and the related IR-SPGR, and the T2 SPACE and T2 SPACE FLAIR sequences. Many spectroscopy sequences also have similar or even greater amounts of "dead time". This substantially relaxes the time constraint on navigators and opens the possibility of acquiring significantly more data for registration.

The PROMO system initially demonstrated this concept by acquiring three orthogonal images using sequential spiral acquisitions [6]. In order to deal with potential out-of-plane rigid motion, this three-plane navigator was repeated several times while iteratively refining the estimate of the subject position relative to the first three-plane navigator in the scan. The PROMO method was first demonstrated in IR-SPGR, and 3D fast spin-echo (FSE) [6], and has subsequently been integrated into single-voxel-spectroscopy (SVS) [7] and arterial spin labeling (ASL) [8] sequences.

PROMO's registration algorithm demonstrates one of the strengths of image-based navigators: it registers the first navigator to an atlas and uses this to generate a brain mask that is used to restrict the volume of interest (VOI) for registration. The ability to restrict the anatomy that is used for registration, (e.g., excluding the neck and jaw) is necessary if rigid motion is assumed for image registration.

Expanding on this idea, EPI-based volumetric navigators (vNavs), were proposed for use in SVS [9], MEMPRAGE, T2 SPACE, and T2 SPACE FLAIR [10]. Unlike the repeated acquisitions of PROMO three-plane navigators during a parent-sequence TR, vNavs are acquired only once per TR. However, since they are a complete volume, one acquisition provides sufficient information for rigid registration. In essence, vNavs can be viewed as interleaving a coarse, repeated-EPI sequence inside the parent sequence, and then performing the same prospective correction as was previously demonstrated in PACE. vNavs address the problem of localization by providing a user interface that allows the scanner operator to select the area that will be tracked. Users are directed to restrict this VOI to just the portion of the head above the jaw and neck, ensuring that only rigid anatomy drives the registration.

Subsequent work has expanded the range of sequences in which EPI-based navigators are applicable. Several more spectroscopy sequences have been proposed with the addition of vNavs (e.g., [11]), and the method was also shown in DWI, where vNavs were acquired after each diffusion volume [12]. Later work has demonstrated methods for acquiring the volume navigator as a series of 2D-encoded slices during the diffusion volumes themselves [13], and a related interleaving strategy for T2 turbo spin-echo (TSE) FLAIR is being presented at this workshop [14]. The insertion of vNavs into 3D-encoded FLASH sequences has also been demonstrated by holding the excitation pulse and TR consistent between FLASH and EPI TRs, allowing them to be arbitrarily interleaved without disturbing the FLASH steady-state [15].

While PROMO and vNavs both acquire large amounts of information to enable accurate image registration, they also both require significant time in which to play out their navigate-and-update block – 240 ms for PROMO [5] and 400 ms for 3D-encoded vNavs [15]. Several groups are now addressing the question of whether whole volumes can be acquired and processed in less time using a variety of acceleration strategies. If possible, this would allow us to expand the range of sequences in which image-based navigators might be applied, or trade the extra time for even more detailed information that might further increase registration accuracy. Key to this development is the increase in computing power available on current scanners that enables more complicated image reconstruction to be performed within the time constraints of prospective motion-correction applications.

Simultaneous multi-slice (SMS) EPI excites and encodes multiple slices simultaneously, and then reconstructs the separate slices by using the spatial information inherent in the sensitivity profiles of high-channel-count receive coils [16]. Initial results using high SMS acceleration factors to substantially reduce the time required to acquire a complete vNav are being presented at this workshop [17].

The use of fat-selective excitation for navigators was initially proposed as a way to avoid disturbing the water signal that is being used for imaging [18]. However, several methods now seek to use the fact that the fat signal in the head is spatially sparse to substantially accelerate the navigator acquisition.

The 3D FatNav strategy combines the spatial sparsity of the fat signal with the local sensitivity profiles of high-channel-count receive coils to enable extreme acceleration (e.g., 64× GRAPPA) [19, 20]. In the initial target application, high-resolution MPRAGE imaging at 7 T, accuracy in the navigator's registration is paramount. With this in mind, FLASH is used to acquire the volumetric navigator and reduce image distortion relative to EPI. Additionally, the 3D FatNav is acquired with 2 mm isotropic resolution, significantly finer than that used in vNavs, to allow more accurate registration. Despite the use of FLASH and a higher resolution, the whole volume is acquired in 495 ms due to the high acceleration.

The 2D FatNav strategy has been demonstrated using a single sagittal EPI slice with 8× GRAPPA following a fat-selective excitation to measure nodding motions and translations in the sagittal plane [21]. The same group has also proposed the Collapsed FatNav strategy which "piggy-backs" on the fat saturation pulse, acquiring three orthogonal planes of EPI in 9 ms. However, unlike PROMO or the single-slice 2D FatNav, which used spatially selective pulses, the new method uses the non-selective fat saturation pulse, and so its three images are orthogonal projections of the complete volume, potentially addressing the problem of "out-of-plane" rotations in a single acquisition. [22].

Summary:

- Image-based navigators can constrain their registration VOI to any sub-region in post-processing, allowing them to be paired with registration algorithms that assume rigid motion.
- Building on the work in self-navigating EPI-based sequences, a range of image-based navigator methods have been developed to meet the requirements of different sequences.
- A key use of image-based navigators was initially in sequences that have significant "dead time" to allow for relaxation.
- Ongoing work demonstrates the potential for image-based navigators to be substantially accelerated, further broadening the range of sequences in which they can be applied.

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