Rapid Motion Detection Using Pre-rotated Baseline Spherical Navigator Echoes

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Introduction: The spherical navigator echo (SNAV) is ideal for tracking rigid body motion in all six degrees of freedom simultaneously [1, 2]. However, current iterative registration algorithms, used to calculate the rotations between two SNAVs, require significant computation time (seconds) and may be trapped in local minima within the search space. These shortcomings limit the feasibility of SNAVs for real time tracking of 3D rigid body motion [3, 4]. The purpose of this study was to evaluate a new approach where a set of pre-rotated baseline SNAVs are acquired and used as templates during the registration of a baseline and rotated positions. This approach, which is verified here in a phantom study, minimizes SNAV processing time by replacing computationally expensive interpolation and registration with rapid subtraction of the rotated-object SNAV from the pre-rotated baseline SNAVs.

Theory: The ability of SNAVs to detect 3D rigid body motion follows from the Fourier rotation and shift theorems. Since rigid body rotation of an object in the spatial domain causes an identical rotation in the frequency domain, the magnitude profiles of SNAVS acquired by rotating the object (Fig. 1a) or rotating the SNAV (Fig 1b) are identical. The registration algorithm starts by collecting a set of pre-rotated baseline SNAVs, Sb{(θx,i, θy,i, θz,i}, where i is the rotation-set index; θx,i, θy,i and θz,i represent the ith rotation applied to the gradients to rotate the SNAV trajectory. To measure the similarity between a physical object rotation (St) and Sb,i we define a cost function cLS(i) = Σ [St(j) – Sb,i(j)]2, where j is the index of the SNAV sample points. The rotation between the baseline and transformed object position is determined by minSb – the rotation that minimizes cLS. The translation between the baseline and transformed position is then determined from the phase differences between St and minSb.

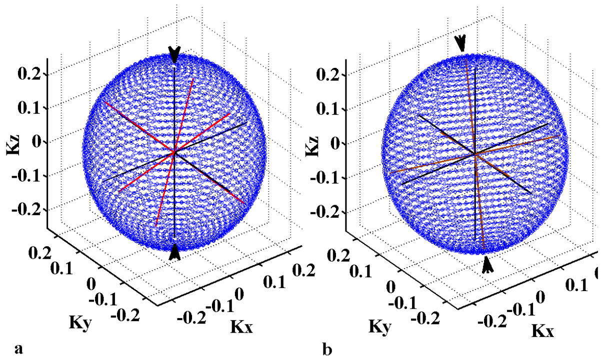

Figure 1. SNAV path (blue) in k-space (unit: cm^{-1}), arrows indicate the poles. a) Object (red) rotated away from the reference position by a rotation operator R(θx, θy, θz), SNAV poles are still parallel with the physical z-axis (black); b) Object stays at the reference position, SNAV is tilted from the physical axis by R(-θx, -θy, -θz).

Methods: A standard fast gradient recalled echo pulse sequence was customized to acquire the SNAV data and modified to accept gradient rotation and translation parameters. All SNAV data were acquired along the entire surface of a sphere with radius Kρ = 0.2 cm-1 in 50 ms (TR = 25 ms) using a two shot approach, collecting 1212 sample points along a hemisphere for each shot. The other parameters were: TE = 1 ms, flip angle = 20°, slab thickness = 30 cm.

Pre-rotated baseline SNAVs were acquired for 512 random rotations generated to cover the following rotation range: ±6° (Pitch, θx), ±6° (Roll, θy) and ±20° (Yaw, θz). The total acquisition time was 25.6 seconds (512*50 ms). The accuracy of motion detection was evaluated using an agarose-gel-filled phantom. To mimic phantom rotation, a second set of 32 randomly rotated SNAVs was collected. Translations in the SI direction were generated by shifting the scanner bed to seven positions covering the range of ± 20 mm. A total of 224 combinations were evaluated.

All experiments were performed on a GE 3.0-T whole-body MRI scanner using a GE 8 ch phased array head coil. The phase alignment method was used to combine the data from all coils into one SNAV data set [5]. Processing of all navigators was performed off-line on a 2-GHz, Athlon processor using MATLAB (MathWorks, Natick, MA).

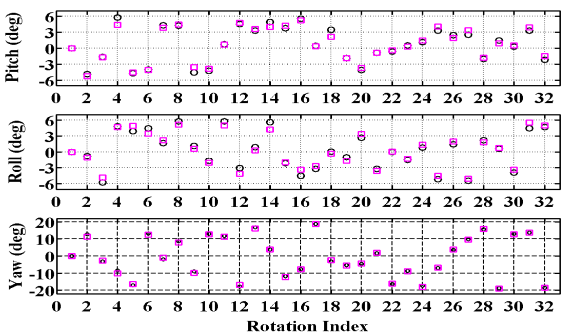

Figure 2. Rotation detection. Circles represent the applied rotation, squares the measured rotation.

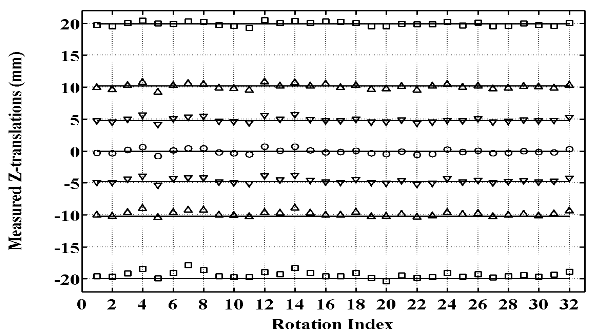

Figure 3. Detecting translation, combined with 32 rotations. The solid lines represent the applied translations.

Results and Discussion: The computation time for determining rotations and translations was 40 ms and 10 ms, respectively, compared to 5-10 s using interpolation techniques. Shown in figure 2 is a summary of the rotation results. The average errors were: 0.0 ± 0.6°, 0.0 ± 0.7° and 0.1 ± 0.6°for pitch, roll and yaw respectively. The measured and expected z-translations are plotted in figure 3. The average error at a translation of ±20 mm was 0.4 ± 0.3 mm. In this study, 512 pre-rotated baseline SNAVs over a large rotation range (±6°, ±6° and ±20°) were used to simulate head motion. To decrease the acquisition time of the baseline set of pre-rotated SNAVs further optimization of the number of pre-rotated data sets is required. New methods being developed to speed up SNAV acquisition (such as: one shot SNAV [1], polar NAV [4], SNAV-GRAPPA [6] etc.) can be combined with the presented motion detection algorithm to provide a rapid, non-iterative and robust tool for 3D rigid body motion detection.

References: [1] Welch, et al., MRM 47:32-41, 2002. [2] Petrie, et al., MRM 53:1080-1087, 2005. [3] Ari and Kraft, ISMRM 14:3195, 2006. [4] Costa et al., MRM 53:150-158, 2005. [5] Debbins, et al., MRM 38:1003-1011, 1997. [6] Liu and Drangova, ISMRM 16:205, 2008.