Selective Least Squares Method with a Region Growing Unwrapping Algorithm for Robust Motion Detection with Navigator Echoes in Magnetic Resonance Imaging

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INTRODUCTION

Patient motion is a significant problem in many MRI applications, including functional MRI, abdominal and cardiac imaging. One approach to compensate for motion effects in MRI is with navigator echoes (NAVs). NAVs measure motion prior to image data acquisition [1] and allow an affine transformation to be applied to the image coordinate system so the object appears stationary during the scan. Linear translation is the main component of patient motion. Accuracy of translation detection algorithms for NAVs is crucial to suppress motion effects. Translation detection with NAVs is straightforward in general but sensitive to noise. An important step in translation detection is removing phase aliasing, which is a challenging problem in the presence of noise. Failure to remove phase aliasing correctly, limits the accuracy of translation detection. In this abstract, we introduce selective Least Squares (sLS) method with a Region Growing Unwrapping (RGU) algorithm to measure linear translation from k-space phase data and we compare our method with currently used Least Squares (LS) methods for low-SNR spherical navigator echoes [2].

THEORY

Translational motion does not alter k-space magnitude, but it introduces linear phase shifts in k-space. Linear translations can be calculated with NAVs by measuring the phase change $\Delta\Phi$ between consecutive NAVs ($\Delta\Phi[k] = \arg\{N1[k]\} - \arg\{N2[k]\}$) and using Fourier shift theorem ($\Delta\Phi = 2\pi\,[k_x\,\Delta x + k_y\,\Delta y + k_z\,\Delta z]$). Subtracting the raw phases of the NAVs can introduce phase jumps (discontinuous) when the phase change is greater than $\pm\pi$. A simple phase unwrapping algorithm, which removes large phase jumps by adding or subtracting 2π, works well for NAVs with sufficient SNR but may introduce false jumps for NAVs with low SNR. A RGU algorithm is proposed here to correct the potentially incorrect phase assignments. Specifically, for each NAV point, the two neighbors are sequentially checked by comparing the phase difference between the neighbor and the point. If the difference is higher than a preset threshold then RGU algorithm "wraps" back this false phase jump. RGU algorithm works effectively even for navigators with high noise content. The Fourier shift theorem is the foundation of translation detection algorithms: translation along any spatial axis in imaging space is proportional to the slope of phase change in k-space navigator data. If the NAV has N sample points, then translation detection solves an over-determined linear system of N equations with 3 unknowns. Previously, LS methods, that minimize the residual error for the over-determined system, have been commonly used for extracting displacement [3]. In LS method, the displacement is measured by non-optimal averaging over all NAV k-space samples. This method is susceptible to noise due to contributions of NAV samples with low SNR, particularly away from the origin of the k-space. Our sLS method removes noisy NAV samples by applying an SNR threshold (σ = %70 SNR) to provide a smoother phase change between adjacent NAV samples. Note that, eliminating noisy NAV samples does not affect the accuracy of translation detection, since the problem is over-determined.

METHODS

Computer simulations were performed to evaluate the accuracy of the proposed sLS with RGU method against currently used LS algorithm. Simulations were performed using in-house software that start with a high-resolution digital brain phantom [4], and creates SNAVs with known translations. A Monte Carlo simulation (20 runs per simulation point = 1000 trials) was performed to estimate the accuracy of the method for 50 different translations. The simulated translations were randomly selected from [-12mm, 12mm] to simulate a wide range of translations. Complex Rayleigh noise was added to each SNAV to operate at different noise levels. The SNAV profiles were processed using both algorithms, and the measurement errors were calculated by subtracting the estimated translations from the true translations. The mean and standard deviation (SD) of these errors were used to compare the algorithms. The simulation results were then experimentally verified by using a water phantom located on a motion platform with known displacement information. The motion platform allowed NAVs to be acquired from the water phantom at different positions.

RESULTS and DISCUSSIONS

Figure 1 shows SNAV phase difference plots with phase jumps greater than $\pm\pi$ (a), a simple unwrapping algorithm introduces false jumps for noisy SNAV points (b), RGU correctly wraps all phase differences into ($-\pi$, $+\pi$) range (c). Figure 2 shows mean and SD of translation detection errors averaged over 1000 Monte Carlo trials at various SNR levels. SNR is defined as the ratio of mean SNAV signal and Rayleigh noise SD. Clearly sLS with RGU outperforms standard LS algorithm, especially at low SNR. The displacements measured with both algorithms on a motion platform are illustrated in Figure 3. For noisy SNAV profile at a higher k-space radius, sLS with RGU produces more robust measurements compared to standard LS algorithm. In summary, we demonstrated that sLS with RGU is a robust method for extracting linear translations from navigators.

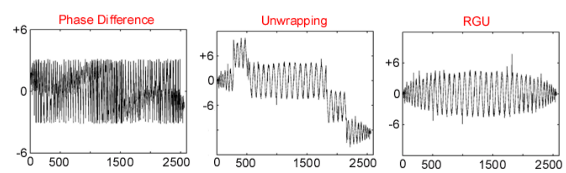

Figure 1: Pre-processing of SNAV phase data prior to application of the translation detection algorithm. Phase difference plots of two SNAVs: a) raw phase difference, b) after unwrapping, c) after RG unwrapping.

REFERENCES

[1] Ehman, et al. Radiology, 173: 255-263, 1989.
[2] Welch, et al., MRM, 47: 32-41, 2002.
[3] Ward, et al. MRM, 43: 459-469, 2000.
[4] Collins, et al. IEEE TMI, 17:463-468, 1998.

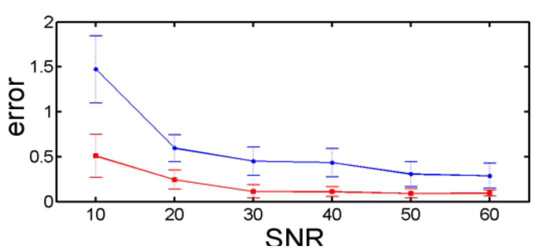

Figure 2: Mean and SD of estimation errors averaged over 1000 Monte-Carlo trials at different noise levels using a simulated SNAV profile for LS algorithm (blue) and sLS with RGU algorithm (red).

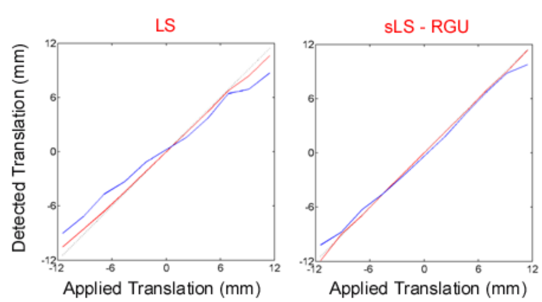

Figure 3: Displacement of a motion phantom detected with a) LS algorithm and b) sLS with RGU algorithm obtained at 2 different SNR levels (blue lines: SNR of 10, red lines: SNR of 50).