PROSPECTIVE MOTION CORRECTION USING NONLINEAR PREDICTIVE FILTERING

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INTRODUCTION

Motion artifacts remain a significant problem in MRI. Retrospective motion correction via post-hoc image registration has two major drawbacks: 1) the images must be re-sampled, which causes blurring; and 2) the procedure cannot correct for the motion that happens *during* the individual k-space acquisitions. Such intra-scan motion results in ghosting and ringing artifacts that generally cannot be corrected for by post-hoc procedures. An alternative approach to motion correction is to correct the images during scanning in near real-time, a technique which is commonly referred to as "prospective motion correction", exemplified by Siemens' PACE method for EPI BOLD acquisitions (1). Here, we present a general framework for prospective motion correction which is capable of adjusting the slice prescription after every MRI readout (e.g. individual EPI slice). This technique, called PROspective Motion correction (PROMO), utilizes the entire history of parameter estimates along with a model of the object's kinematics to recursively estimate the object's position (in three dimensions) in real-time. The approach can be adapted for use with a wide range of imaging methods, including single- and multi-shot EPI, PROPELLER, 2-D and 3-D conventional spin echo, fast spin echo, and inversion prepared gradient echo sequences.

THEORY

Real-time motion detection in MRI can be formulated as a nonlinear sequential estimation problem. This formulation allows the use of nonlinear predictive filters, such as the Extended Kalman Filter (EKF) (2) for online inference. Nonlinear predictive filters consist of a *process* and *measurement* model. For motion tracking in MRI, the process and measurement models can be described by [1] and [2], respectively.

$$\mathbf{p}_{i+1} = f_i(\mathbf{p}_i, \mathbf{w}_i) = \mathbf{p}_i + \dot{\mathbf{p}}_i \Delta t + \ddot{\mathbf{p}}_i \Delta t^2 / 2 + \ldots + \mathbf{w}_i \quad [1]$$

$$\mathbf{y}_i = h_i(\mathbf{p}_i, \mathbf{v}_i) = vec(R(\mathbf{M}(\mathbf{p}_i)\mathbf{x})) + \mathbf{v}_i \quad [2]$$

$$\mathbf{x} \in R^{4xn}, \mathbf{M}(\mathbf{p}_i) \in R^{4x4}$$

[1] is a kinematic description of the object using its position ($\mathbf{p}$), velocity ($\dot{\mathbf{p}}$), and acceleration ($\ddot{\mathbf{p}}$). The exact form of [1] depends upon the kinematic assumptions and the sampling rate Δt . Here, we truncate [1] to first order (constant position model). The position $\mathbf{p}$ parameterizes a rigid-body affine transform $\mathbf{M}(\mathbf{p})$ which maps the current image $\mathbf{y}$ to a fixed reference $R(\mathbf{x})$. [2] is a nonlinear re-sampling function which interpolates $R(\mathbf{x})$ at the predicted position. Recursive estimates of $\mathbf{p}$ are obtained using the EKF filter update equations. The filter bandwidth is controlled by adjusting the magnitude ratio of the process noise covariance $\mathbf{Q}; \mathbf{w} = N(0, \mathbf{Q})$ to measurement noise covariance $\mathbf{R}; \mathbf{v} = N(0, \mathbf{R})$. We refer to this ratio as the "smoothness factor" (SF).

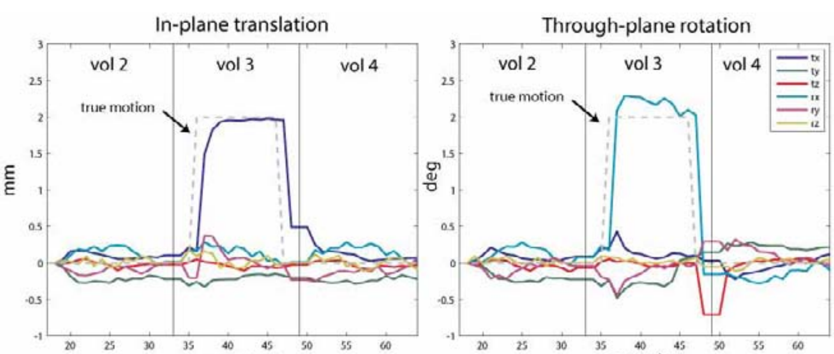

Figure 1.

METHODS

We used simulated and real MRI datasets to test the validity of the PROMO method for motion estimation. In the first experiment, we simulated an EPI time-series by re-sampling a single axial gradient echo EPI volume (TR/TE: 2sec/19.7msec, image matrix: [64 64 16], voxel size (mm): [3.125 3.125 5]) collected on a 1.5 T Signa Twin Speed system (GE Healthcare Technologies, Milwaukee, WI) four times using linear interpolation. In the middle of the third volume, 10 slices were translated along the positive x-axis (left/right) by 2mm. White random noise (2% of signal magnitude) was then added to each voxel. This procedure was then repeated for motion in the remaining five degrees of freedom resulting in six total time-series datasets (one translation and one rotation in each of the three cardinal axes of Euclidian space). The rotation magnitude was 2 deg. PROMO was used to estimate motion in each of the six time-series datasets using the first volume of each as the reference. In a second experiment, a pineapple was scanned using a PROPELLER sequence (TR/TE: 6sec./108.3msec., num blades: 26, image matrix:[28 28 25], voxel size (mm): [7.86 7.86 3]) collected on a GE 3.0T Signa EXCITE system. During acquisition, the pineapple was translated 3mm along the B_0 direction (z-axis) by programming periodic (6 sec.) shifts in the patient table. Prior to running PROMO a control parameter was added to [1] to account for the individual blade rotations. The first blade in the series was used as the reference image for PROMO. In both experiments, Matlab and C implementations of PROMO were run on a Dell Precision Desktop (Xeon Woodcrest 3Ghz processor, 4G RAM).

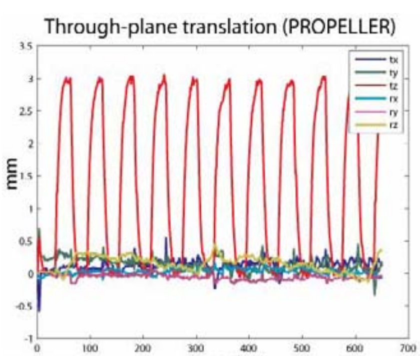

Figure 2.

RESULTS

Results of the EPI simulations are shown in Figure 1. Only translation along and rotation around the x-axis are shown (all other datasets show similar results). PROMO estimates (solid lines) are shifted by one sample with respect to the true motion (dashed gray line) in order simulate online feedback delay. The average time per estimate was 56.2 and 18.7 msec. for the Matlab and C implementations, respectively. Results of the PROPELLER experiment are shown in Figure 2. Here, only the PROMO estimates are shown. In this experiment, the average time per estimate was 26.3 and 8.6 msec. for the Matlab and C implementations, respectively.

DISSCUSION/CONCLUSIONS

Our results demonstrate that the PROMO method provides accurate estimates of in-plane as well as through-plane motion during scans, with greatly reduced latency relative to existing methods. Although the current results apply only to self-navigating EPI and PROPELLER acquisitions, we are in parallel working on applying the PROMO method to other sequences, including commonly used clinical 2-D and 3-D acquisitions, using separate navigators. If successful, this approach may largely eliminate artifacts associated with subject motion, thus reducing data loss, and extending the diagnostic use of MRI to a wider range of subject populations.

REFERENCES

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