Predictive Filtering for Improved Robustness in Prospective Motion Correction

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PURPOSE

A variety of external motion tracking systems have been used for prospective motion correction (PMC) in brain MRI in recent years. Despite high nominal tracking accuracy, current systems have a number of limitations, especially when used in clinical settings with uncooperative patients[1]. One important limitation is the latency between the measurement of head pose and the corresponding slice-volume adjustment. Latencies cause PMC errors during high-velocity motion, regardless of the accuracy of the tracking system. In this work, we combined predictive filtering with retrospective motion correction to account for the latency of an optical tracking system during a prospectively corrected MRI scan.

METHODS

Experiments were performed on a Siemens 3T Tim Trio scanner, equipped with a Moiré Pattern Tracking (MPT) system. MPT consists of a single in-bore optical camera which tracks a 15mm^2 target affixed to the subject's forehead. The tracking system has an absolute accuracy of <0.1mm/deg across the measurement volume, and was operated at 70 frames per second for this study. Images were acquired with a 2D gradient-recalled echo (GRE) sequence, modified to receive MPT tracking data and perform PMC prior to each excitation. GRE imaging parameters were TE/TR=5/70ms, FA=35^0, 1x1x4mm^3 voxels, 7 slices.

A latency of $\Delta t = 30ms$ was previously measured for our tracking system. In order to account for this latency, an online Kalman filter was implemented which uses raw MPT data to estimate true 6-DOF motion parameters (3 translations + 3 rotations, $\vec{x}_{filt}$) and their first and second derivatives (i.e., velocities & accelerations, $\vec{v}_{filt}$, $\vec{a}_{filt}$). Since the motion parameters are lagged by Δt, the pose used for online PMC was determined by extrapolating the filtered motion parameters forward in time: $\vec{x}_{PMC} = \vec{x}_{filt} + \vec{v}_{filt}\Delta t + 0.5\vec{a}_{filt}\Delta t^2$ [Eq.1], where $\vec{x}_{PMC}$ is the applied correction. Since high-velocity motions may produce significant residual pose errors despite prediction, retrospective phase corrections and conjugate gradient (CG) reconstruction were performed in Matlab to correct translational and rotational errors.

Two healthy volunteers were scanned twice each, with four GRE images per session. Subjects were instructed to lie still for the first scan, and perform periodic "head shake" motions (z-rotation, ~1Hz) during the remaining three scans. The images acquired during motion were acquired in three modes: 1) no PMC (uncorrected), 2) standard PMC (no prediction), and 3) PMC with predictive filtering described by Eq. 1. Retrospective corrections were applied to the 2 PMC images, for a total of 6 images per scan session.

The efficacy of predictive filtering was measured as follows: First, the true 6-DOF motion trajectory was determined by time-shifting the measured trajectory by Δt, and subtracted from the applied corrections to obtain PMC errors, $\delta\vec{x}_{PMC}$. The magnitude of $\delta\vec{x}_{PMC}$ was computed by treating mm and degrees on equal footing, and the root-mean-square (RMS) of $|\delta\vec{x}_{PMC}|$ across the acquisition was used to quantify total PMC errors. Additionally, images were rated by an experienced neurologist (blinded to the motion-correction protocol) as follows: 0 – **No** artifacts, 1 – **minimal** artifacts, 2 – **moderate** artifacts and 3 – **severe** artifacts.

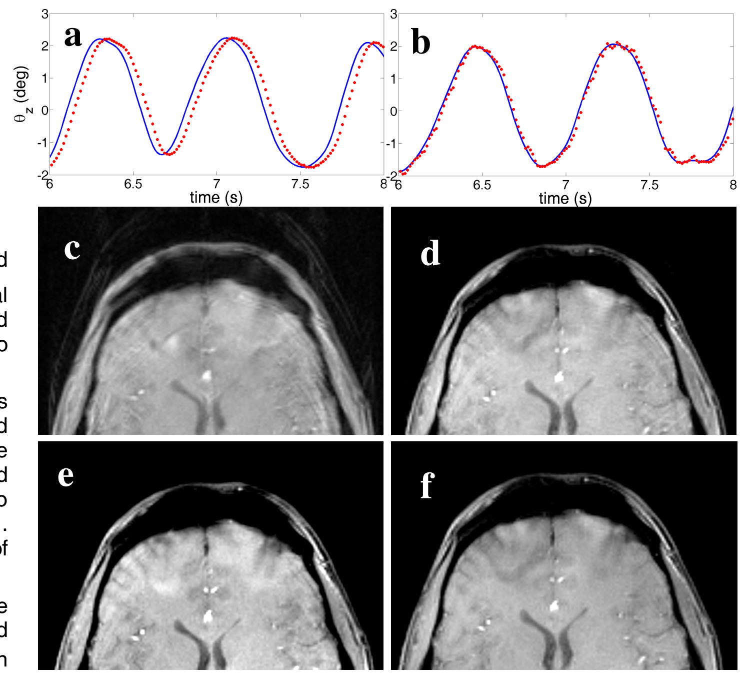

Figure: *PMC scans acquired with predictive filtering OFF (left column) and ON (right column).* ***Top row:*** *motion plots, with the true trajectory in blue and PMC updates shown as red dots. In* ***a****, the latency results in large residual errors, whereas in* ***b****, prediction reduces PMC errors.* ***Center row:*** *Images acquired with the PMC updates shown in* ***a*** *&* ***b****. Improved PMC results in reduced ghosting in* ***d*** *as compared to* ***c****.* ***Bottom row:*** *The same images as* ***c*** *&* ***d****, with PMC errors retrospectively corrected.*

RESULTS

RMS velocity magnitudes varied by <8% within each session, indicating that subjects were able to reproduce similar motions. However, one subject consistently performed larger-amplitude motion at higher velocities (mean velocities for the two subjects were 26mm/s and 63mm/s). Predictive filtering reduced PMC errors from 2.26±1.27mm/deg to 0.74±0.33mm/deg, a significant difference (paired t-test, p=0.05); see Figure, **a** versus **b**. The PMC images from one session are shown in the Figure (**c** – **f**), and the mean ratings for all images are displayed in the Table. All images acquired with predictive filtering ON were rated better than or equal to the images with filtering OFF. In every case, retrospective corrections improved the rating of both filtered and unfiltered images.

Correction Mode	**Mean Score**
No motion	0
PMC OFF	3.25
Standard PMC	2.75
Filtered PMC	2.25
Standard PMC + retro. correction	1.375
Filtered PMC + retro. correction	1.25

DISCUSSION

Maclaren et al. have previously used combined PMC + retrospective corrections to account for tracking noise[2]. Our system has substantially lower noise, but the latency is large enough to cause large residual errors (>5mm) during high-velocity motion; therefore we added prediction. Our results show that predictive filtering can greatly mitigate latency-derived PMC errors. Furthermore, by reducing PMC errors, prediction improves the efficacy of retrospective CG corrections by reducing the size of Nyquist-violating "holes" in k-space.

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