Head pose prediction for prospectively-corrected EPI during rapid subject motion

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INTRODUCTION Prospective motion correction using an external tracking device is an effective technique for motion correction in fMRI [1]. It has advantages over image-based correction methods [2], which require full volume coverage to compute motion parameters in a full six degrees of freedom (6DOF). The ultimate goal of this project is to use prospective correction to perform fMRI experiments during significant head motion. However, when motion is rapid, latency delays in the system lead to significant slice misregistration. The aim of this work is to determine whether motion prediction can mitigate this problem.

METHODS Kalman filtering has been shown in simulations to improve tracking data for prospective motion correction in brain imaging [3]. Here, we incorporate such a system into the prospective motion correction pipeline, using a Kalman filter with a position-velocity state model, operating in 6DOF. To compensate for the total latency delay in the system (Fig. 1), the state is predicted in advance by TL ms. Filtering and prediction is performed online in less than 1 ms. The 'tracking system latency' component of TL was measured using a FLASH sequence incorporating both tracking data and MR navigators.

To test the approach, head tracking was performed using an optical infrared system (ARTtrack3, Advanced Real-Time Tracking GmbH, Germany), operating at 60 fps during imaging (matrix size: 64×64, TR: 100 ms, TE: 50 ms, slice thickness: 4 mm, single slice) of a healthy volunteer on a 3 T Magnetom Trio (Siemens Healthcare, Germany). The subject was instructed to perform repeatable left-to-right sinusoidal motion, with a period of approximately 5 s, during the acquisition of three different time series: (a) without prospective correction; (b) with prospective correction [4]; and (c) with both prospective correction and pose prediction.

To quantitatively compare results, the image registration method used by PACE [2] was applied to all images in each time series to generate residual motion values. To validate the resulting data, image registration was also performed using the 'Realign' module in SPM8 (Welcome Dept. of Imaging Neuroscience, UK).

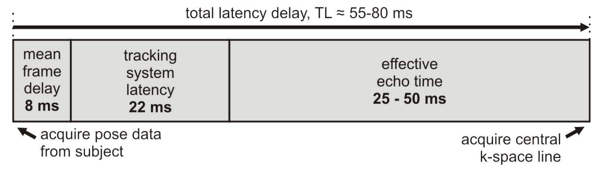

Fig. 1: Delays between frames, in data processing, and in the sequence itself, result in a latency delay, TL, between the acquisition of the latest pose information and the centre line in k-space. This results in residual motion errors in an EPI time series after prospective motion correction.

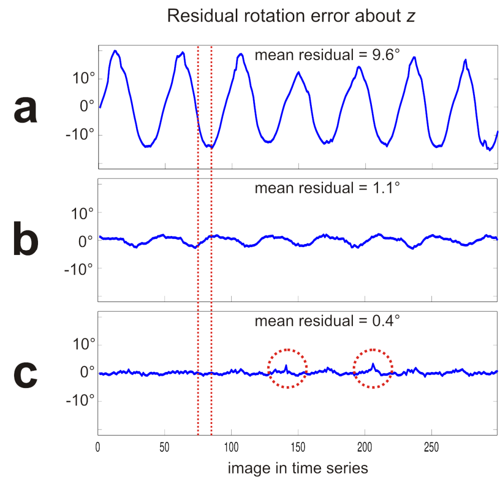

Fig. 2: Residual rotation errors from an EPI time series with (a) no motion correction, (b) prospective correction, and (c) prospective correction with pose prediction. The red circles indicate a 'spike' caused by overshoot of the filter during rapid change in head velocity.

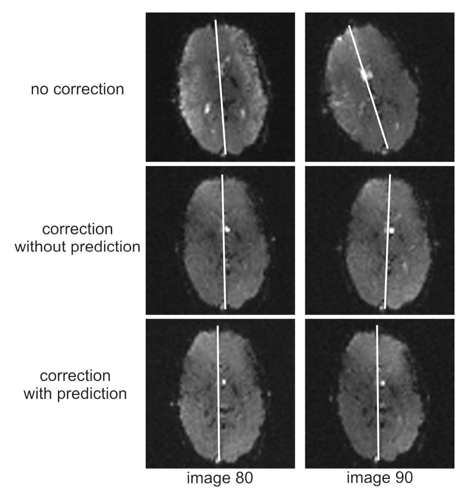

Fig. 3: Example images from the time series plotted in Fig. 2, corresponding to the red vertical lines. Including motion prediction as part of prospective motion correcting reduces residual errors in image position and orientation.

RESULTS AND DISCUSSION Examination of the tracking data showed that the motion of the subject was approximately equal in each experiment. Peak rotational velocities achieved in each cycle were around 27 degrees/s about the *z*-axis. Motion was present in all other degrees of freedom, but to a lesser extent. Fig. 2 shows residual motion from PACE for each of the three experiments in a single degree of freedom (rotation about z). Residual motion data obtained using SPM8 (not shown) were very similar, confirming that PACE was functioning correctly for this data set. Without correction, the pseudo-sinusoidal motion of the subject is clearly visible (a). This is greatly reduced when prospective correction is enabled (b). In (b), the mean peak residual error in each cycle corresponds well to the approximately 2.2 degrees that one might expect by multiplying the latency delay (TL = 80 ms) with the mean peak velocity (27 degrees/s). Residual errors are reduced further when using motion prediction (c). Images from two points in the time series are shown in Fig. 3.

Several 'spikes' are visible in the residual error curve in Fig. 2c (see red circles) after prospective correction with prediction. These are caused by an 'overshoot' in prediction, when head motion direction suddenly reverses. Results might therefore be improved by including acceleration information into the Kalman filter model, at a cost of greater computation time.

This work requires knowledge of the latency delay, TL. This incorporates the value for the 'frame delay' (Fig.1), which is assumed here to be 8 ms. This is the mean value: the frame delay can range from near zero to a maximum of 16.7 ms (60 fps). Exactly timing information would enable this value to be known precisely for each frame, which would slightly improve prediction.

Although the influence of the motion prediction method on fMRI activation has not been studied here, improving image alignment will naturally improve BOLD sensitivity [1]. However, uncorrected B0 distortions, which distort the frontal part of the brain in the corrected images in Fig.3, are problematic. This could be addressed by applying the method in [5].

In conclusion, this work shows that motion prediction using a Kalman filter results in a significant reduction in residual motion in an EPI time series involving rapid, large motion.

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