Integration of an External Motion Tracking System with the MR Scanner for Highly Accurate Real-Time Prospective Motion Correction

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Introduction

Image quality in MRI may be critically disturbed by subject motion. A number of MR-based approaches, such that orbital(1) or spherical(2) navigators, has been developed to reduce the motion sensitivity of the standard 2D and 3D imaging techniques. Navigators, however, are not compatible with every imaging method because of possible steady state perturbations and measurement time considerations. Employing external motion tracking hardware for motion correction in MRI(3-7) is a promising approach. However, up to now it failed to meet the requirements on both the accuracy placed by high resolution imaging and the overall system latency to enable prospective corrections. The goal of this work was to seamlessly integrate a high-end motion tracking system with the MR scanner and to optimise its accuracy by the development of a novel cross-calibration method. In addition, a method to determine experimentally the total latency of the measurement system is proposed.

Methods

The stereoscopic motion tracking system was interfaced to a Magnetom Trio 3T system (Siemens Medical Solutions, Germany). The gradient echo (GRE) and turbo spin echo (TSE) sequences were modified to allow changes of the imaging volume position during the k-space acquisition. The tracking system ARTrack1 (Advanced Realtime Tracking, Germany) was able to measure positions of multiple targets consisting of retro-reflective spheres with an accuracy of 0.1mm (RMS) at a frame rate of 60Hz. The cameras with integrated infrared flashlights were positioned at the feet end of the scanner inside the magnet room (Fig. 1). In order to minimise delays the tracking system was connected to the internal Ethernet of the MR instrument and the communication was implemented on the real time control unit of the scanner.

The transformation to the scanner coordinate system was determined by a newly developed cross-calibration procedure: First, the positions of water-filled reflective spheres were defined from MR images (3D GRE, resolution 1mm^3, TE/TR=1.8/4.9ms, flip angle 12º) and by the tracking system in order to calculate an initial estimate of the coordinate transformation. In the next steps this transformation was iteratively refined. The transformation error was detected from two 3D GRE images of a structured gel-filled phantom acquired with the motion correction enabled (resolution 2mm^3, TE/TR=1.5/4.6ms, flip angle 10º). During the delay between the repetitions the phantom was rotated by 180º. The residual shifts and rotations detected by realigning these images were used to calculate correction terms for the coordinate transformation in the plane normal to the axis of rotation. In order to find all components of the coordinate transformation the 180º rotations needed to be performed around at least two orthogonal axes. Typically 2 to 3 iterations per axis were required.

The total delay in the whole acquisition and correction loop was calculated using the following setup. Four retro-reflective spheres were fixed to a plastic disk, which could freely rotate around the horizontal axis. Three of the spheres were filled with water to become MR-visible. The disc was linked by a belt transmission to an air-driven turbine. The axis of rotation was aligned with the z-axis of the magnet; the centre of rotation in the plane of the reflective spheres was placed in the magnet isocentre. First, a static 2D image of the spheres was acquired. In the subsequent measurements performed with prospective motion correction the air turbine was driven with different angular velocities. For a constant angular velocity the latency in the feedback loop results in an apparent rotation of the object by an angle equal to the product of the delay and the angular velocity. In order to measure this angle the images acquired in presence of rotation were realigned to the still image.

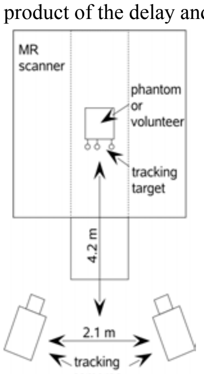

__Fig. 1.__ Setup of the tracking system

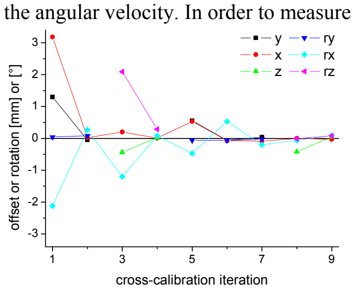

__Fig. 2.__ Residual shifts and rotations detected after the corresponding calibration iteration. Iterations 1, 2, 5, 6, 7 were performed in the trans-versal orientation and iterations 3, 4, 8, 9 in the coronal plane.

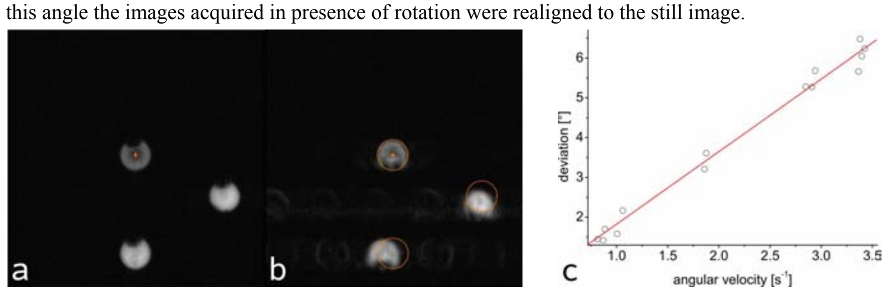

__Fig. 3.__ Delay measurement in the entire acquisition and correction loop. (a) Stationary image of the 3 reflective spheres filled with doped water. (b) Image acquired in presence of rotation with a constant angular velocity. The positions of the spheres from the still image (a) are marked with dotted lines. In this particular case the measured angular deviation was 5.3° and the angular velocity calculated retrospectively from the motion tracking data was 2.85s^{-1}. (c) The results of 14 experiments with different rotation velocities along with the fit line. The slope of the line is the measure of the latency.

Results

In Fig. 2 the progression of the iterative cross-calibration procedure is visualised. After 9 iterations (about 30 minutes) the calibration errors were reduced from several millimetres to below 0.1mm and 0.1º.

Results of the latency measurement are presented in Fig. 6 and described in detail in the caption. From the slope of the fit (Fig. 6c) the delay in the entire feedback chain was determined to be 32±1 ms.

The effectiveness of the prospective motion correction under extreme conditions of strong motion is demonstrated in phantoms in Fig. 4.

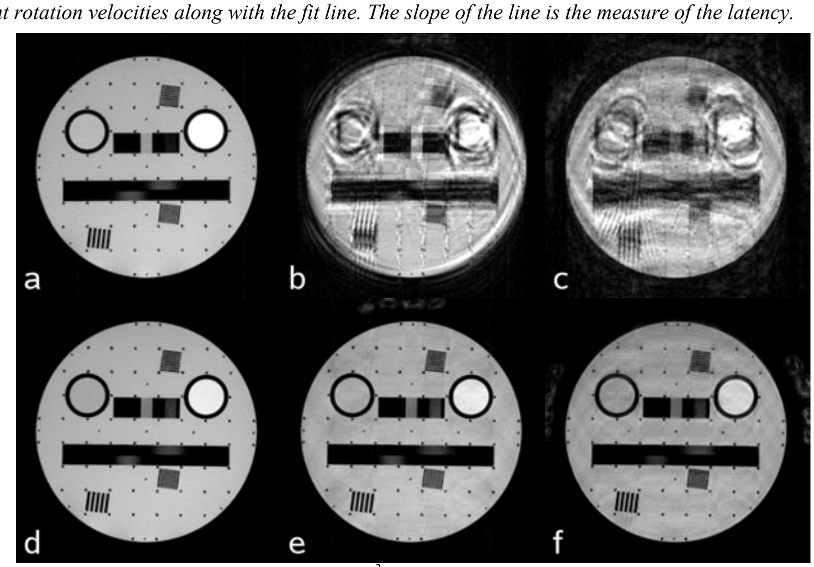

__Fig. 4.__ 2D SE acquisition (resolution 1mm^2, slice thickness 4mm, TE/TR=7.3/200ms). Images (a), (b) and (c) acquired without correction; images (d), (e) and (f) with motion correction under different conditions: (a) and (d): no motion, (b) and (e): ±2.5º axial rotation, (c) and (f): ±15º. The phantom was moved manually; operator's fingers can be seen in the images.

Discussion

To our knowledge, this study presents the fastest and most accurate external real-time motion correction(3-7). The implementation allows for minimal delays based on a precision high speed tracking system and a highly efficient implementation on the scanner. The system latency is to a large part defined by the average update rate of the camera system (half the frame rate). The novel cross-calibration approach enables an unprecedented accuracy of the tracking data. The proposed motion correction scheme is compatible with a multitude of MR sequences including high resolution MRI, where such accuracy is mandatory for successful prospective correction.

References: [1] Fu ZW, et al. MRM 34:746-753 (1995). [2] Welch EB, et al. MRM 47:32-41 (2002). [3] Eviatar H, et al. ISMRM 1999; #269. [4] Tremblay M, et al. ISMRM 2002; #1409. [5] Zaitsev M, et al. ISMRM 2004; #2668 [6] Marmurek J, et al. ISMRM 2005 #2243 [7] Tremblay M, et al. MRM 53:141-149 (2005).