Full 3rd Order Real-Time Shim Feedback for Field Stabilization and its Application in Brain MRI at 7T

Yolanda Duerst[1], Bertram J. Wilm[1], Benjamin E. Dietrich[1], David O. Brunner[1], Christoph Barmet[1,2], Thomas Schmid[1], Signe J. Vannesjo[1], and Klaas P. Pruessmann[1]
[1]*Institute for Biomedical Engineering, University of Zurich and ETH Zurich, Zurich, Switzerland,* [2]*Skope Magnetic Resonance Technologies, Zurich, Switzerland*

Introduction

Well-defined spatial and temporal behavior of the magnetic field evolution is crucial for successful MR experiments. However, hardware imperfections (e.g. eddy currents, self-induction in gradient coils, temperature drifts) as well as physiological effects (e.g. breathing, cardiac motion) limit the achievable field stability. In some cases it is possible to correct for effects caused by field fluctuations with post-acquisition correction techniques, by extracting the field fluctuations from the acquired data [1] or from independent measurements [2, 3]. Nevertheless, field changes during data acquisition can also lead to inherent information loss, due to increased T_2* decay (e.g. by through-plane dephasing) or misapplied RF pulses, that cannot be resolved by data processing. Solutions to this problem have been advised by real-time correction of B_0 field changes either using a dynamic B_0 reference scan and a breathing belt for chest motion detection [4] or direct field measurement with an NMR field probe [5]. The latter concept, similar to field locks for NMR systems [6], has recently been extended to higher-order real-time feedback to correct for field fluctuations using multiple ^{1}H NMR field probes [7]. Thereby spatio-temporal field instabilities stemming from various sources, independent of the specific MRI/MRS sequence and sample can be compensated. To concurrently apply field stabilization with the MR sequence, decoupling between imaging and probe data is necessary. In this work we present a full 3rd order, concurrent feedback implementation using ^{19}F NMR field probes and show the first application to high resolution brain imaging.

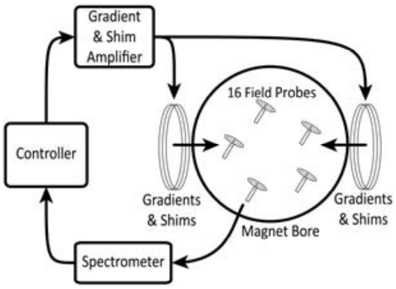

Fig. 1– Schematic of the feedback-loop. Field measurements are fed into a controller which drives gradients and shims to correct for unwanted field fluctuations.

Methods

Controller - The total magnetic field in the scanner bore at the probes' positions and points in time t_k is modeled as the sum of three terms: the target field pattern as governed by the sequence, field fluctuations, and corrections produced by the gradients and shims in order to stabilize the total field: $\boldsymbol{B}_{tot}(t_k) = \boldsymbol{B}_{target}(t_k) + \boldsymbol{B}_{fluc}(t_k) + \boldsymbol{B}_{corr}(t_k)$, where each vector entry is the field strength at the position of one probe. The controller's objective, to keep the error $\boldsymbol{e}(t_k) = \boldsymbol{B}_{target}(t_k) - \boldsymbol{B}_{tot}(t_k)$ small, is achieved by means of a discrete proportional-integral (PI) controller: $\boldsymbol{B}_{corr}(t_k) = K_p\,\boldsymbol{e}(t_k) + K_i\sum_{\kappa=0}^{k}\boldsymbol{e}(t_\kappa)$. In order to produce this correction field, gradients and shims are driven by applying correction voltages, $\boldsymbol{u}(t_k)$, to the corresponding amplifiers where it is assumed that the field produced is a linear combination of the individual responses: $\boldsymbol{B}_{corr}(t_k) = \mathbf{C}\cdot\boldsymbol{u}(t_k)$. The steady state response C_{ij} denotes the effect of the jth shim at the position of probe i and is calibrated prior to the experiment. In each step the voltages $\boldsymbol{u}(t_k)$ are calculated as a linear-least squares solution which was regularized to avoid voltages that exceed the allowed amplifier input.

Hardware - The real-time shim feedback system (Fig. 1) was based on 16 fluorine NMR field probes [8] that were placed cylindrically around a 32 channel head coil insert (Nova Medical) into the bore of a Philips 7T Achieva scanner (Philips Healthcare, Cleveland, USA) equipped with a full 3rd order spherical harmonic shim system (Resonance Research Inc., Billerica, USA). The probes' signals were received by a stand-alone spectrometer [9] for digitization and field strength determination by a linear fit of the phase evolution. Subsequently, the required correction voltages were calculated as described above and constantly applied to the gradient and shim amplifiers until the next cycle of the control loop determined new values. The current implementation allowed for an update time $T_{up} = t_k - t_{k-1} = 0.1$sec which, by manual tuning of K_p and K_i, led to a control loop bandwidth of about 2Hz.

Imaging - The feedback system was used for correction of breathing-induced field oscillations during a high resolution T_2*-weighted brain scan (adapted from [10]: TR/TE/flip angle = 800ms/25ms/45°, voxel size = 0.3x0.3x2mm, FOV = 230x230mm, 8 slices).

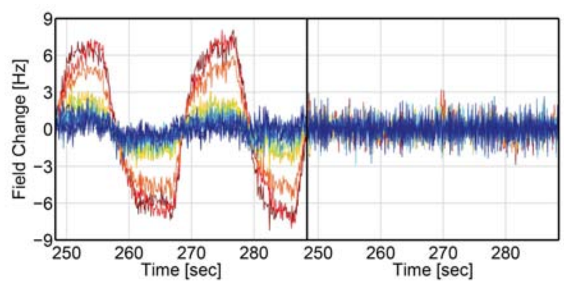

Fig. 2 – Field changes due to breathing in all 16 probes without (left) and with (right) feedback.

Results

In the uncorrected case, oscillations in the probes' field evolution reflect the breathing pattern (Fig. 2, left). The observed peak-to-peak amplitude depends on the probe's position showing the spatial variation of the field caused by respiratory motion. Turning on feedback control largely removes the breathing related field perturbations (Fig. 2, right). The achieved field stabilization leads to a considerable improvement in image quality by removing image ghosting and signal cancellation artifacts (Fig. 3).

Conclusions

We present a first implementation of a full 3rd order real-time shim feedback system. The control loop achieved robust field stabilization of breathing induced field perturbations which significantly enhanced image quality of a commonly used T_2*-weighted gradient-echo scan which otherwise strongly suffers from breathing artifacts.

By improving the control loop to higher spatial order and higher temporal resolution, real-time field feedback holds promise to correct not only for external field fluctuations and physiological mechanisms but also for hardware imperfections and thus reduce requirements on magnet, gradient and shim hardware.

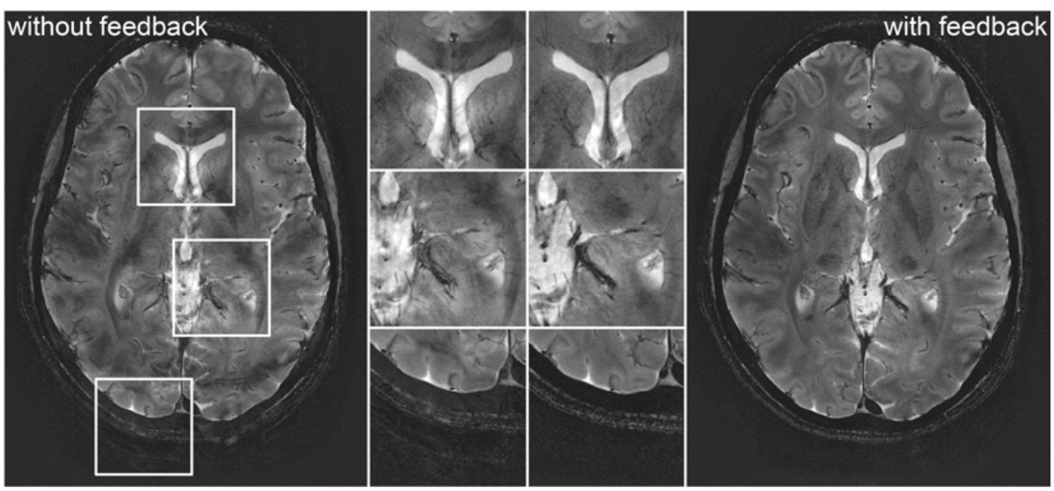

Fig. 3 – Comparison of image quality without (left) and with (right) feedback. Enlargements show strong reduction in signal loss (top), blurring (middle), and ghosting (bottom) in the corrected case.

References

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