Real-Time Shim Feedback for Field Stabilization in Human MRI Systems

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Introduction

The stability of the magnetic field strength is a crucial prerequisite for most MRI/MRS experiments. However field changes stemming from various sources such as temperature drifts, physiological motion, or any other external effects can severely degrade the experimental results. In some cases it is possible to retrieve information about unwanted field changes from the experimental data itself [1] or by means of separate measurements [2, 3] and remove related artifacts during data reconstruction. However, even if such information can be accurately obtained, field changes during the experiment can lead to an irreversible loss of information (e.g. by increased T2* decay or RF pulses being applied off-resonance). This problem can be addressed by real-time field adjustment, which has been demonstrated, e.g., for respiratory effects which can be parameterized by readings from a breathing belt [4]. In the present work, it is proposed to achieve real-time field control based on direct field measurements in analogy to deuterium locks [5] as used for B_0 stabilization in NMR spectrometers. The required field observations are performed with miniature NMR field probes [2, 6], whose signals are used to control the shim coils of a whole-body MR system in real-time. Thereby it is possible to compensate fields from arbitrary external sources independent of the used MRI/MRS sequence and sample.

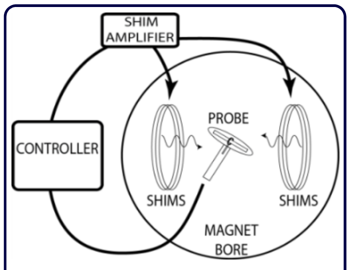

Fig.1 - Schematic of the feedback loop.

Methods

Hardware: The real-time shim feedback system (Fig.1) was based on up to six NMR field probes [6] that were placed approximately octahedral in the bore of a Philips 7T Achieva scanner (Philips Healthcare, Best, NL) equipped with a full 3rd-order spherical harmonic shim system. The probes' signals were received by a controller for digitization (14Bit, 250 MHz analog to digital converter, NI5761, National Instruments, Austin, USA), demodulation and filtered decimation to 1 MHz bandwidth [7]. From the digitized raw signals the field strength at each probe position was extracted by a linear fit of the phase evolution over 4ms at a time. Subsequently, the required shim corrections were calculated as described below and fed back to the shim amplifiers via a digital to analog converter.

Control: The total magnetic field in the bore ($B_{tot}(t,\vec{x})$) at time t and spatial coordinate $\vec{x}$ can be described as the sum of three independent fields: $B_{tot}(t,\vec{x}) = B_{ref}(\vec{x}) + B_{ext}(t,\vec{x}) + B_{shim}(t,\vec{x})$, where $B_{ref}(\vec{x})$ is a reference field pattern measured with the probes prior to the scan, $B_{ext}(t,\vec{x})$ is a spontaneous deviation from $B_{ref}(\vec{x})$ induced by uncontrollable sources, and $B_{shim}(t,\vec{x})$ is the field produced by the shim coils.

For calibration, a shim response matrix C was determined by applying a known voltage $a_i(t)$ to the i^{th} shim amplifier and measuring the field response in the k^{th} field probe: $B_{shim}(t,\overrightarrow{x_k}) = \sum_{i=1}^{N_{shims}} C_{k,i} \cdot a_i(t)$. The control loop operates on the shim currents $a_i(t)$ in discrete time steps of Δt. In each iteration step the required shim voltages $a_i(t)$ are calculated to minimize the field deviation $\Delta B_{measured}(t,\overrightarrow{x_k}) := B_{tot}(t,\overrightarrow{x_k}) - B_{ref}(\overrightarrow{x_k}) = B_{ext}(t,\overrightarrow{x_k}) - B_{shim}(t,\overrightarrow{x_k})$ by solving $\Delta a_i(t) = \sum_{k=1}^{N_{probes}} (C^{-1})_{i,k} \cdot \Delta B_{measured}(t,\overrightarrow{x_k})$ and accordingly readjust the applied voltage.

Stability of the implemented discrete integral controller [8] was ensured by setting the integral gain to the heuristically determined value of 0.1 and by choosing a maximal update rate of 10 Hz ($\Delta t = 0.1s$) to allow for the shim fields to settle [9].

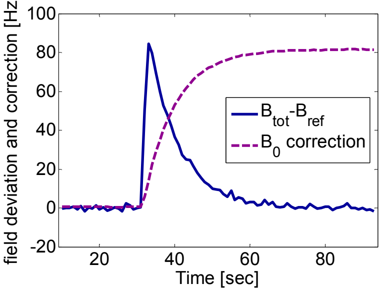

Fig.2 - Effect of moving a water bottle on B_0: Deviation of the measured field (B_{tot}) from the previously measured reference (B_{ref}) (solid line), and the field response expected for the applied shim currents (dashed line).

Results

In a first experiment the setup was evaluated for the compensation of relatively strong effects that were induced by moving a water filled bottle (0.3l) next to the volume of interest, using only one field probe and feedback to the B_0 shim coil. In this experiment, the update time Δt was set to one second, yielding a slow, smooth feedback response (Fig.2). The induced change of about 84 Hz in the measured B_0 field (solid line) was gradually and automatically compensated for by the feedback system's voltage output corresponding to a ramp-up of the B_0 shim to 84 Hz (dashed line).

In a second experiment, single-probe B_0 control was used to stabilize the field following a gradient intensive scan which is known to cause B_0 drifts [10]. The B_0 shim coil was used to correct every Δt = 500ms for a total drift of about 2 Hz over a time of 22 minutes (Fig.3, thick line) while the measured field was kept constant (Fig.3, thin line).

A third experiment was performed to demonstrate the correction of higher-order fields created by a person moving next to the scanner bore. All six field probes were used in this setup to control the six shim coils indicated in Fig. 4, using fast update at Δt = 100ms.

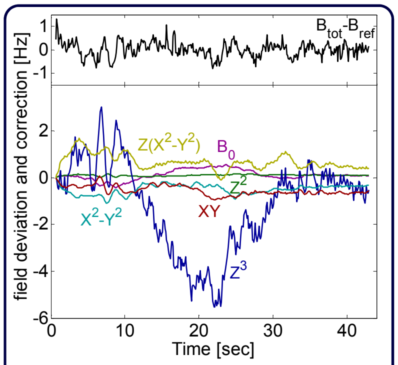

Fig.4 – Person entering and leaving the scanner room: The measured field deviation in one out of the six probes (top) and the field produced by the different shim coils to correct for the field distortions (bottom).

Conclusions

The present work reports the implementation and initial results of real-time B_0 and shim feedback control in an MRI system, using NMR field probes and a stand-alone controller. Successful field stabilization has been achieved in three experimental situations of varying effect strength, update rate, and spatial order of the field control.

By further increasing the number of probes and controlled shim coils, even more complex field fluctuations may be compensated for. Faster feedback response will likely be achieved by refining the control electronics and software and particularly by advancing the control approach, which was limited to straightforward integral control with conservative gain settings in this first setup. More advanced control methodology may also incorporate desired field dynamics such as gradient or shim sequences to improve their fidelity in the presence of field perturbations.

Feedback field control in in-vivo MRI holds promise for addressing a range of remaining issues related not only to external field fluctuations, magnet drifts and other hardware imperfections but also to physiological mechanisms such as breathing, bulk motion and cardiac action. Ultimately, the capability to react flexibly and reliably to arbitrary field fluctuations may even reduce requirements on magnet, gradient and shim hardware and thus reduce the cost of high-performing MR systems.

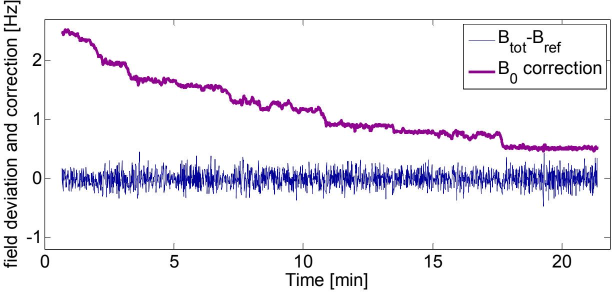

Fig.3 – Field stabilization after gradient intensive scan: The measured field B_{tot} is kept constant at the level of the reference B_{ref} (thin line) by applying a voltage to the B_0 shim that produces a correction of the field drift (thick line).

References

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