Faster Feedback Field Control using Shim Pre-Emphasis

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INTRODUCTION

Real-time feedback field control has recently been shown to improve MR imaging [1] and spectroscopy [2] at high field strength. The field control system enables real-time adjustment of gradient and shim terms to correct for field changes due to, e.g. temperature drifts and physiological motion. If not corrected for, these field deviations cause inconsistencies in spatial encoding but also increased T_2* decay and off-resonant application of RF pulses which cannot be corrected retrospectively. So far the implementation of the system [1] relied on the simplified assumption that the shims react instantaneously to inputs and that coupling between the different shim channels can be neglected. Both assumptions are generally violated to a certain degree – primarily in higher-order shim channels [3] – which can derogate the performance of multivariable feedback loops [4]. To enable faster and more robust field control we present the incorporation of gradient and shim pre-emphasis including cross-terms in a real-time field feedback system.

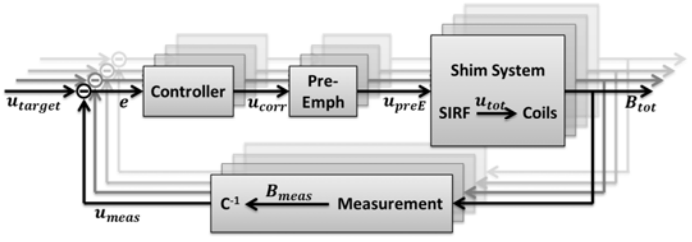

Fig. 1: Block diagram of the field control loops.

METHODS

Real-time shim feedback control (Fig. 1) was implemented on a Philips 7T Achieva scanner (Philips Healthcare, Cleveland, USA). Field sensing was performed using 16 fluorine NMR field probes [5] and a separate spectrometer [6]. In each feedback cycle the measured field values were transformed to shim amplitudes by multiplication with the inverse of the steady state shim response (**C**) [1]. Subsequently the deviation between target and measured shim amplitude were calculated for each shim channel and fed to the controller. As detailed below, the ***Controller*** calculates the required correction voltages. ***Pre-emphasis*** is applied to the resulting shim demand before being sent to the input of a full 3rd-order spherical harmonic shim system (Resonance Research Inc., Billerica, USA) and to the gradients as first order shims, hence controlling 16 spherical harmonic terms.

Controller – Feedback control was implemented by 16 independent control loops (Fig. 1). A proportional-integral (PI) controller was used to determine the correction voltage for each shim channel at time t_k: $u_{corr}(t_k) = K_c\left(e(t_k) + 1/T_i \sum_{k'=0}^{k} e(t_{k'})\right)$ to minimize the error, $e(t_k) = u_{meas}(t_k) - u_{target}(t_k)$, of the measured to the targeted shim amplitude. The proportional constant K_c and the integral time T_i were used to tune the controller and the control loop ran at a rate of 10 Hz.

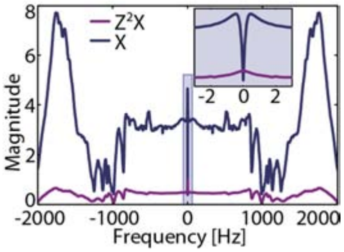

Fig. 2: Measured SIRF amplitude for input in Z2X. Self-term in red and cross-term to X in blue. Amplitudes are normalized to the self-term DC response.

Pre-emphasis – The shim impulse response function (SIRF, Fig. 2) relates an input at the i^{th} shim amplifier to the response measured in the j^{th} shim channel: $O_j(\omega) = SIRF_{ji}(\omega)\, I_i(\omega)$. The individual SIRFs together make up a matrix with the cross-term responses as the off-diagonal elements: $\boldsymbol{O}(\omega) = \boldsymbol{SIRF}(\omega)\, \boldsymbol{I}(\omega)$. The measurement of the SIRF matrix is shown in reference 3. A digital pre-emphasis was obtained by multiplying the inverse of the SIRF matrix with the desired system response: $\boldsymbol{P}(\omega) = \boldsymbol{SIRF}^{-1}(\omega)\, \boldsymbol{H}(\omega)$, where a raised cosine function was used as desired frequency response of the self-terms: $\boldsymbol{H}(\omega) = rc(\omega) \cdot \mathbb{1}$ [3]. All self-terms and the dominating cross-terms (Z3→Z, Z2X→X, and Z2Y→Y) were taken into account in the pre-emphasis calculation.

Experiments – To compare field feedback with and without pre-emphasis, closed loop responses to a step change of a target shim configuration was observed for both implementations. Two target shims were tested: One 2nd-order (ZX) and one 3rd-order (Z2X) shim term to also assess cross-term effects. The feedback rate was 10 Hz; 5 field measurements were interleaved with the feedback to allow for observation of the field evolution between shim updates.

To demonstrate the benefit of fast field feedback, high resolution T_2*-weighted gradient echo imaging (TR/TE/flip angle = 300ms/25ms/45°, voxel size = 0.3x0.3x1.5 mm, FOV = 240x190 mm, 3 slices) of the brain was performed with and without field control with pre-emphasis aiming to correct for breathing induced field changes.

RESULTS

The feedback response to a step change without pre-emphasis shows a slow initial rise due to eddy currents which misleads the feedback to overshoot (Fig. 3a). For shim channels with strong cross-terms (e.g. Z2X→X, Fig. 3b) field control without pre-emphasis results in strong oscillatory disturbances. With pre-emphasis, eddy current effects including cross-term responses are compensated, which results in an accelerated response to changes in the target field (Fig. 3c & d). The measured fields reached and stayed within 5% of the target after 0.1 s (for ZX) and 0.3 s (Z2X) as compared to 0.5 s and 1.4 s, respectively in the non-pre-emphasis case. This is also reflected in the root-mean-squared errors over all probes (Fig. 3e & f). In vivo experiments show considerably increased image quality in T_2*-weighted sequences (Fig. 4) when applying field control. Ghosting and signal dropout artifacts due to deep breathing of the subject were reduced.

CONCLUSION

We presented enhanced field feedback control by incorporating gradient and shim pre-emphasis. The approach also included cross-term pre-emphasis, thereby the individual shim channel responses are decoupled which justifies the use of parallel feedback loops. The achieved increase in stability of the control loop allows for more aggressive tuning of the PI controller, and thus accelerates the achievable field control. Further increase in the feedback bandwidth will be useful, e.g., to correct for rapid limb motion. By decreasing the latency of the control loop, hence increasing the feedback rate, the setup may as well be used to dynamically control the shim configuration during a scan by asking for specific target values. This would allow for a robust implementation of slice-wise shimming or MR experiments that employ higher-order encoding fields.

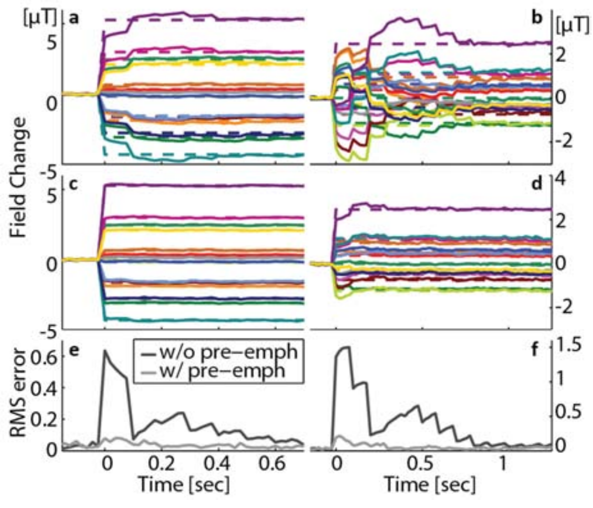

Fig. 3: Step response of the closed loop feedback system for a step in ZX (a,c,e) and Z2X (b,d,f). Without pre-emphasis (a,b) and with pre-emphasis (c,d). Measured field evolutions in 16 probes are shown as solid lines; corresponding target values are dashed (a-d).

REFERENCES

[1] Duerst et al., Proc.ISMRM 2013 [2] Wilm et al., MRM 2013 [3] Vannesjo et al., MRM 2013 [4] Gasparyan, Wiley 2008 [5] Barmet et al., MRM 2008 [6] Dietrich et al., Proc. ISMRM 2012

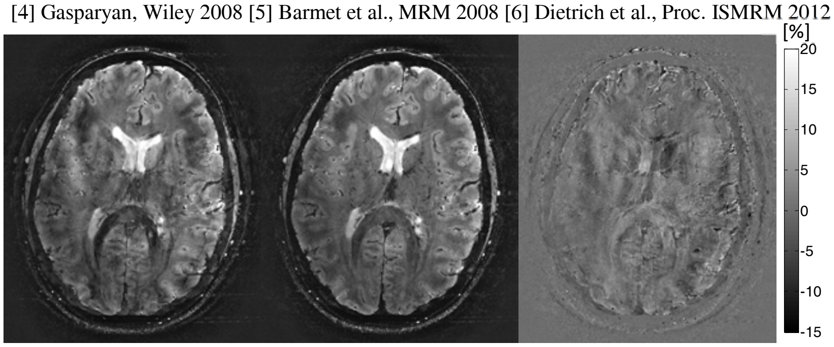

Fig. 4: T_2-weighted gradient echo image acquired during deep breathing. Without real-time field feedback (left) and with feedback including pre-emphasis (middle). The difference image (right) is scaled to the maximum of the non-feedback image in percent.*