Multi-purpose, multi-nuclei, multi-channel data acquisition system

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ABSTRACT: Traditionally, MR systems are designed to acquire data from a single nucleus at a time. However, new modalities like magnetic field monitoring (MFM) [1,2] and functional metabolic imaging, like hyperpolarized ^{13}C [3], would benefit from simultaneous/interleaved multi-nuclei data acquisition. In MFM, replacing the NMR samples with a nucleus different from the imaging one would eliminate the interferences between NMR probes and imaging elements completely, in practice. With multi-nuclear data acquisition system, both metabolic and standard proton images could be acquired interleaved. In this abstract, we present a receiver constructed from commercial off-the-self products. Apart from the RF front-end (e.g. preamplification and anti-alias filtering), the heterodyne receiving [4] (Fig.1) is implemented with LabVIEW software (National Instruments, Austin, TX). We show results that prove the applicability of the receiver for MFM experiments, as well as for standard ^{1}H imaging. The receiver can work individually, or be used simultaneous with the standard clinical MRI scanner.

MATERIALS AND METHODS: To complete an eight-channel receiver, four PXI based, two channel, high speed, 14-bit digitizer boards have been stacked together into a chassis running under a standard PC system (products PXIe-5122, PXI-1065 & PXI-8130, National Instruments, Austin, TX). The digitizers provide sampling timebase rate up to 100 Msamples/s. Without compromises made to the sampling rate, the PXI-express busses can transfer the acquired data to PC RAM for data processing and storing.

The NMR signal bandwidth ranges approximately from tens of kilohertz up to 1 MHz at the highest. With proper band-pass filtering before digitizing, a high rate of undersampling can be performed. On the other hand, by increasing the sampling bandwidth, one can significantly relax the filter requirements before the RF front-end. Respectively, some preamplification of the NMR signal should be performed to minimize the noise contribution from the ADCs (analog-to-digital converter). A various selection of commercial low noise preamplifiers can be applied for this purpose.

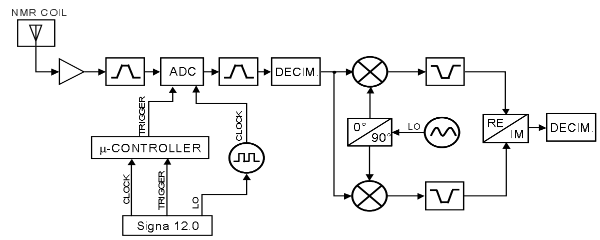

Fig.1 Schematic of the self-made receiver system for acquisition of NMR signals. Except the preamplifier and band-pass filtering, the signal processing is done with software.

After the ADC, the rest of the digital signal conditioning is performed software-wise. To increase the speed of signal processing, decimation to reduce redundant data points before down-conversion is done. Before the decimation, the signal is filtered to the desired bandwidth of the MRI signal. This is to avoid overlapping of undesired frequency components and is implemented with finite impulse response (FIR) band-pass filters. After the filtering and decimation, the signal is divided into real and imaginary components by multiplying the signal with software sine and cosine waves at the selected local oscillator frequency (e.g. quadrature detection). Based on the center frequency set, the signal bandwidth and the ADC sampling rate, an algorithm to solve the local oscillator frequency in combination with optimal intermediate sampling rate (e.g. the sampling rate after the first decimation) has been developed. After the quadrature detection, the final decimation eliminates the rest of the redundant (now complex) data points and sets the NMR center frequency to zero.

The signal bandwidths, local oscillator frequencies, and decimation factors can be adjusted for each channel separately, enabling flexible, simultaneous acquisition of multiple frequencies. If the acquisition system is applied in parallel/interleaved with normal imaging sequences of a standard MRI system (for example in MFM), synchronization and timing between systems should be provided. In our case, we take the "start sequence trigger" signal provided from the MRI system cabinets (Signa Excite 12M4 3T, GE Healthcare, Milwaukee, WI). The trigger is routed to the data acquisition system via 16-bit microcontroller, which is taking care of the desired timing. The microcontroller shares the same master clock with the system (10 MHz commonly). As normal analog down-conversion locks the phases of the transmitter and receiver signals, a method for software down-conversion to maintain the phase coherence has to be applied. In our work, we apply the analog RF LO-signal from the MRI system to phase-lock with a separate voltage controlled oscillator (VCO). The output clock of the VCO is a divisor of the LO-frequency, and when applied as the sampling clock of the ADCs, the phase-coherency is preserved within the level of jitter of the VCO.

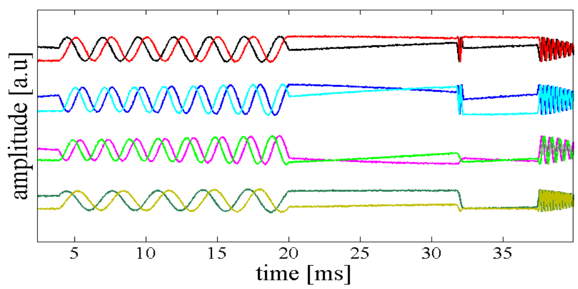

Fig.2 Tracked NMR signals from four ^{2}H field monitoring probes during a calibration scan. Real and imaginary are shown separately. Notice the crushers at the very end of the sequence.

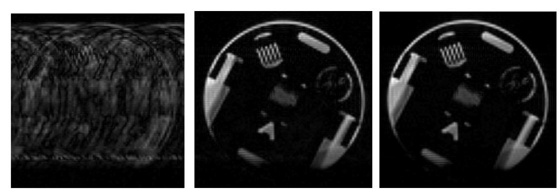

Fig.3 Gradient echo images (256x128) acquired with the self-made data acquisition system (leftmost) and GE Signa 12M4 receiver (rightmost). The phase in-coherency with the self-made receiver is compensated in the center image.

RESULTS AND DISCUSSION: With the separate receiver system accompanied with MFM probes, the field performance can be monitored beyond the normal image acquisition window (Fig.2). Now the center frequency can be adjusted separately for each of the probes, which are placed commonly around the ROI, well off from the isocenter. The minimizing of the frequency offset brings an advantage, as the phase-unwrap algorithm is now less likely to fail. Respectively, one can adjust the bandwidths of each probe to match the magnetic field swing (e.g. frequency swing) across the particular sample. This can be used to increase the SNR of the probes closer to the isocenter.

For a second test, a quadrature birdcage transmit/receive coil tuned to proton frequency (GE Healthcare, Milwaukee, WI) was placed around a resolution phantom for imaging purposes. A GE Signa Excite 12M4 3T (GE Healthcare, Milwaukee, WI) MRI scanner was set to perform a gradient echo imaging sequence. First, the received signal, was connected to the separate self-made receiver after the 1st amplification stage and the image-reject filter. For comparison, the sequence was repeated with the standard Signa12M4 receiver. The bandwidths and sampling windows were matched in both cases. The reconstructed images based on the raw data were compared (Fig.3). Artifacts similar to ghosting can be observed in the image acquired with self-made receiver. This is expected to be caused by the relatively high jitter (~250 ps) of the VCO implemented, and thus insignificant phase coherency between consecutive phase encoding steps. After regaining the phase coherency with post processing, comparable image quality and SNR were observed (~78 with Signa receiver, and ~51 with the self-made one without any SNR optimization). When done in parallel to data acquisition, the software based DSP does not compromise with imaging speed.

With the system presented, one gains increased level of flexibility and modality in the use of the hardware. Changes in the functionality can easily be done with software, and hardware is not only dedicated for MRI purposes alone. For example, it can be applied for simultaneous ECG/EEG monitoring or system RF tracking.

REFERENCES: [1] G.F. Mason et al., Magn. Reson. Med.,vol.38, p.496-492,1997, [2] K.P. Pruesmann et al., ISMRM 2005:p.681 [3] D. Mayer et al., Neuroimage, Vol. 35(3), pp. 1077–1085, 2007, [4] R. Hartley, US Patent 1,666,206, 1927