An Open Source Low-Cost NMR System

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Introduction: In recent years a great deal of effort has been put into developing small, low cost MRI and NMR magnet and coil arrays. These systems are aimed at a wide variety of applications, such as volume imaging [1-3], 1D depth imaging [4], material and fluid characterization [3, 5-6], biosensors [7-8], and even spectroscopy[9]. While the focus of such research is on the development of the magnets and coils, a hardware platform for conducting NMR experiments is also required. Such platforms often consist of repurposed equipment with costly, excessive features, or undesired limitations [8,10]. Here we present a versatile, low cost prototype NMR system using only off-the-shelf components. Real time sequencing and sampling is handled by an Arduino platform, which interfaces with an external computer which runs a MATLAB-based user interface and analysis program. The entire system, excluding the power supply and host computer, is hand-built using only off the shelf components (aside from the Arduino), with a total price under $400. The design of the system is open source, and can be accessed online at [11].

Materials and Methods: *System control*: For ease of development, we chose an Arduino Uno, based on a Atmel ATMEGA328 MCU, as the real-time control platform. The Arduino is coded with a general-purpose CPMG sequence [12], which can be configured to give T_1, T_2, ρ_0, and diffusion (D) weighted data. After configuring sequence parameters using MATLAB via USB, the Arduino executes the desired CPMG sequence, samples the NMR signal, and sends the sampled data back to MATLAB for analysis. *RF signal chain*: The RF signal chain is designed to be broadband, making it easy to use over a wide range of frequencies. An AD9851 DDS from Analog Devices is used to synthesize the RF carrier, which is modulated by the Arduino into rectangular pulses and amplified by a 150W current mode class D amplifier similar to [13]. Different flip angles are realized through variation by of the pulse durations (5-100us), amplifier supply voltage (15-30V), and output attenuation (10-20dB, $Z_0 = 50\Omega$). The transmit amplifier has a bandwidth of 2MHz, requiring adjustment for large changes in operating frequency. The system uses a broadband TR switch to operate a single transmit/receive coil. Any simple TR coil matched to 50Ω can be used. During signal reception, the RF signal from the coil is amplified with a gain between 45-75dB, and downconverted directly to baseband via a mixer stage. The local oscillator signal for the mixer is also provided by the DDS. The RF receive chain has an overall bandwidth of 5-80MHz, with an overall noise figure of 4.5dB. A narrowband LNA and TR switch can be substituted to improve the NF to 1.5dB, at the expense of manual tuning. A baseband filter after the downconverter adds another 36dB of gain, and also selects an appropriate signal bandwidth with a second order lowpass filter (normally 20KHz-100KHz). An external 16 bit ADC (AD7685) samples the peak of each spin echo. A block diagram of the system is shown in figure 1. The minimal achievable inter-echo time is approximately 100us, due to recovery of the receive chain, coil ringing, and due to communication speed limitations of the Arduino [14]. This system was designed for use in NMR experiments in which a static gradient is present; therefore, no gradient control functionality was included. *NMR Experiment*: We used the fringe field of a Siemens Espree 1.5T system to perform a diffusion experiment using a variable TE CPMG system similar to [6]. A sample with known D (1mL DI water, $D = 2.299 \times 10^{-5}\,\mathrm{cm}^2/s$ [15]) is used to estimate the effective gradient (|G|) strength over the sample, as well as its T_2, by performing a model fit using the following equation: $1/T_{2a} = \gamma^2 G^2 T_E^2 D/12 + 1/T_2$ [16].

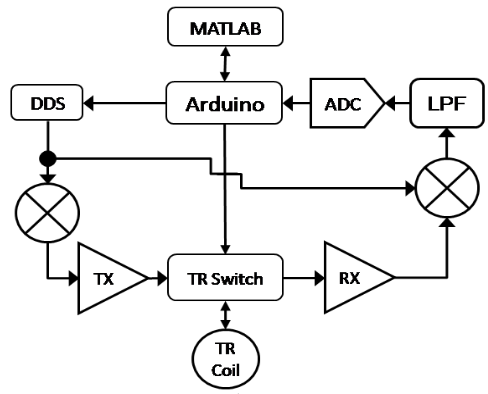

Figure 1: Block diagram of the NMR system

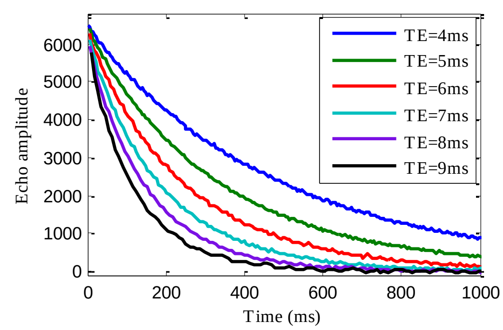

Figure 2: Plots of CPMG echo amplitude for water recorded using the NMR system in the fringe field of a Siemens 1.5T scanner. The apparent $\mathbf{T_{2a}}$ of each signal is weighted by TE and self diffusion D [16]. Each curve is a single echo train.

Results: Figure 2 shows the raw data from the experiment described above. Fitting the apparent T_2 (T_{2a}) of each curve and its TE to the diffusion model resulted in an estimated |G|=85mT/m and T_2=2.17s, both of which are within expectations.

Discussion: Our results demonstrate a working NMR instrumentation platform which is versatile enough to perform simple NMR experiments with a variety of magnets and frequencies. Though not presented here, the system has been used on several other magnets, including low field permanent magnet arrays in the range of 196-335mT. Only minor adjustments to the hardware are necessary when changing operating frequency. A variety of simple NMR experiments, including measurements of T_1, T_2, ρ_0, and D, can be performed. With a proper enclosure, the system could easily fit within a shielded enclosure of less than 4 liters. Thus the system could be used as an educational tool for the study NMR and MRI in a lab setting. The project is open source, with details on design and application available at [11].

References: [1] Casanova F, et al. J Magn Reson.2003 Jul;163(1):38-45. [2] Perlo J, et al. J Magn Reson. 2004 Feb;166(2):228-35. [3] Blümich B, Magn Reson Imaging. 2005 Feb;23(2):197-201. [4] Perlo J, et al. J Magn Reson. 2005 Sep;176(1):64-70. [5] Rata DG, et al. J Magn Reson. 2006 Jun;180(2):229-35. [6] Casieri C, et al. J Magn Reson. 2003 Jun;162(2):348-55. [7] Haken R, et al. J Magn Reson. 2000 Jun;144(2):195-9. [8] Galante A, et al. IEEE 2011 May:429-32. [9] Perlo J, et al. J Magn Reson. 2006 Jun;180(2):274-9. [10] Chang WH, et al. Magn Reson Imaging. 2006 Oct;24(8):1095-102. [11] http://ccir.case.edu/Research/mri/lowcostmr, 2011. [12] Meiboom S and Gill D. Rev. Sci. Instrum 1958;29:688-91. [13] Gudino N, et al. *ISMRM*. 2010; 43. [14] Anferova S, et al. Concepts in Magn. Reson. 2002;15:15 – 25. [15] Bruker. *Bruker Almanac Analytical Tables*, 2011. [16] Haacke E, et al. *MRI*. 1999: p626. Wiley & Sons.