NMR Hardware and Desktop Systems

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Abstract. Modern magnetic resonance imaging (MRI) systems consist of large numbers of complex, high cost subsystems. Often this makes them impractical for use as routine laboratory instruments, limiting their use to hospitals and dedicated laboratories. However, recent advances in the consumer electronics industry have led to the widespread availability of inexpensive radio-frequency integrated circuits with exceptional abilities. We have developed a small, low-cost MR system derived from these new components. When combined with inexpensive desktop magnets, this type of MR scanner has the promise of becoming standard laboratory equipment for both research and education. This paper summarizes our progress in developing the transceiver for such a scanner and presents a performance comparison between the prototype and a commercial Varian SIS-85 system. Preliminary results on standard spin echo images (TE=40 msec, TR=1 sec) show comparable SNR to the commercial system

INTRODUCTION

The potential of MR microscopy has been demonstrated by a growing number of investigators [1-5]. Using magnetic fields strengths of 2.0 Tesla and above, researchers have demonstrated imaging resolutions of as little as 6x6x6 microns [3], and are suggesting even further improvements. However, these studies have used superconducting magnets, necessary to obtain field strengths over 2.0 Tesla. Recent advances in permanent magnet technology, principally improvements in energy density and numerical design techniques, have made low-field magnets an attractive alternative for MRI system design [6]. A prototype 0.22 Tesla desktop magnet with a sample size of over 1 inch has been constructed in the Magnetic Resonance Systems Laboratory at Texas A&M, using less than $2400 in magnet material [7]. In addition to low-cost magnets, the high cost of the electronics used in commercial MRI systems magnetic resonance imaging (MRI) systems must be reduced in order for MRI systems to become routine laboratory instruments. For applications not requiring the stringent requirements of a clinical system, we have found that MR transceivers can be inexpensively built using commercially available components. This paper summarizes our progress in developing the transceiver for a low-cost desktop MR imaging system that will be particularly useful in education and research environments.

METHODS

The objective of this project was to demonstrate an inexpensive MR system which would be able to image small volumes with high resolution on dedicated, low-field MR magnets such as that reported by Cole, Esparza, and Huson [6.7]. In doing so, we required that our system be capable of imaging sample volumes of 1-in. (25.4 mm) diameter, in fields of 0.25 Tesla or less, with a resolution of 75x75x200 microns. A block diagram of the MR spectrometer designed for this project is shown in Figure 1. Solid lines in Fig. 1 indicate MR signal paths while dashed lines are control signals. A description of each block follows in the paragraphs below.

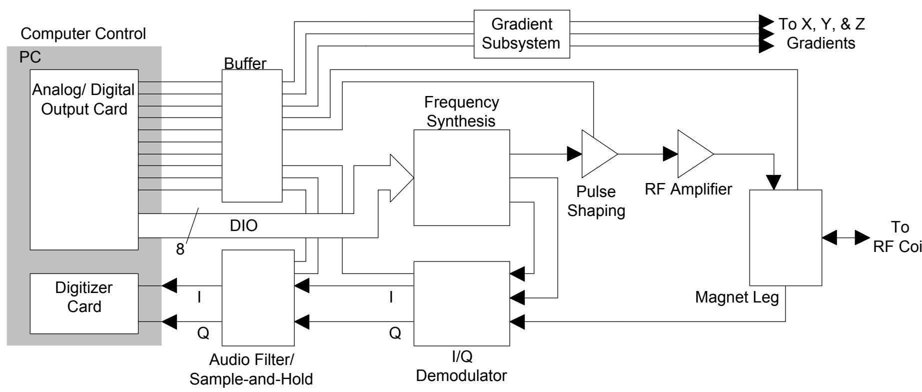


FIGURE 1. Block diagram of prototype desktop MR system transceiver.

The computer control block was implemented using a Pentium-II, 300 MHz PC. The analog/ digital output and the digitizer are standard PCI-bus data acquisition cards available from National Instruments. Software for controlling the transceiver was written in LabView[8].

The buffer block is necessary to protect the analog/ digital output card from damage by possible system transients and other over-current conditions. The digital portion of the buffer module consists of the 74HCT244, an octal buffer chip which is available from several semiconductor manufacturers. The analog portion is comprised of eight, National Semiconductor, LM6221 high-speed analog buffer chips.

The gradient subsystem consists of three gradient amplifiers and three gradient filters. Each of the three filters is a simple, LC low-pass filter with a cutoff frequency of 100 kHz. The amplifiers are each made from the National Semiconductor, LM12 high power op-amp, using a current amplifier circuit taken from the manufacturer's data sheet. Each amplifier is capable of throwing ±10 amps into the low resistance, high inductance load presented by a gradient coil. A basic schematic of one gradient amplifier, with additional input circuitry for applying DC offsets on the gradient amplifier output, is shown in Figure 2.

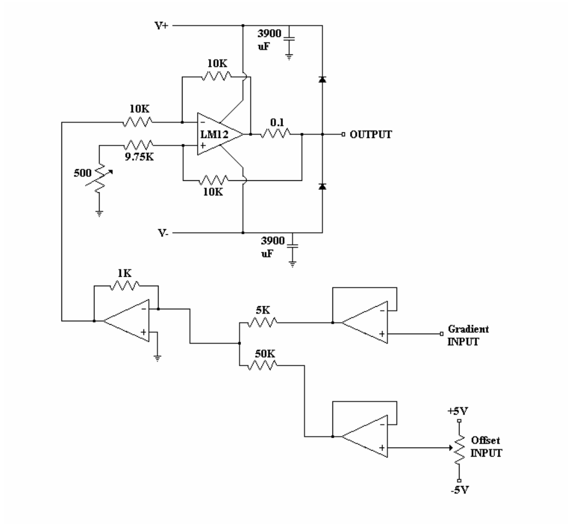


FIGURE 2. Schematic diagram of a simple and inexpensive gradient amplifier with offset control.

The frequency synthesis block is used to create both the RF transmit frequency and the two local oscillator signals required by the I/Q demodulation block. This is done by three direct digital synthesis (DDS) circuits. Each DDS circuit consists of an HSP45102 and an HI5735 chip from Intersil. The HSP45102 is a 12-bit, numerically controlled oscillator (NCO) while the HI5735 is a high-speed, 12-bit, digital-to-analog converter (DAC). Together, these two chips make a waveform synthesis circuit which can generate 0-20 MHz sine waves having both 0.009 Hz of frequency tuning resolution and an output phase controllable in 90° increments.

Pulse shaping is accomplished by using the National Semiconductor CLC5523. The CLC5523 is a wideband, variable gain amplifier on a single chip. The gain of the device may be varied between 0 and -80 dB by applying an external control voltage. In conjunction with the phase control feature of the DDS chips, this provides a convenient method for amplitude modulation for shaped pulses. An evaluation module board for this part is available from the manufacturer.

To implement the RF amplifier block, several low-cost, linear, RF amplifiers are commercially available in many different power levels for the frequency band spanning 1.8-30 MHz. These amplifiers may be obtained from any one of the many distributors of products to CB and Ham radio enthusiasts. For imaging the small sample volumes anticipated in our application, a 20-Watt amplifier manufactured by Henry Radio was used. The amplifier does not have blanking, a requirement for MRI, so an external p-i-n diode blanking switch was added at the amplifier output.

The magnet leg, shown in Figure 3, is comprised of an active p-i-n diode blanking switch, a passive quarter-wave T/R switch, a low-noise preamp, a band-pass filter, a low-pass filter, and two low-noise gain stages. The active p-i-n diode switch, passive T/R switch, and band-pass filter were all constructed from inexpensive components in our lab. For the low-noise preamp, the Miteq AU-1519-7480 amplifier, which has 60 dB of gain from 2-300 MHz and a maximum noise figure of 1.2 dB, was used. The low-pass filter is a Mini-Circuits BLP-10.7 (with a cutoff frequency of 10.7 MHz). Finally, the two low-noise gain stages were constructed using the Mini-Circuits MAR-

4SM and MAR-6SM single-chip RF gain blocks. To further simplify matters, these MAR-xSM amplifiers are available in kit form from RadioShack.com for a modest price.

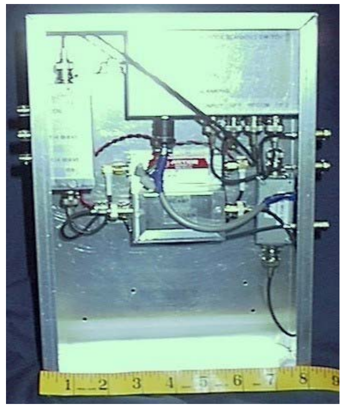


FIGURE 3. Magnet leg block in prototype desktop MR system transceiver.

To provide I/Q demodulation of the MR signal, the Analog Devices AD607, a 2-stage down-conversion receiver on a single chip, was used. The AD607 takes RF inputs at frequencies up to 500 MHz and demodulates them down to baseband at its I and Q outputs. Available on a populated evaluation module board, the chip requires only two local oscillator signals (provided by the frequency synthesis block in our transceiver), a supply of 5-VDC power, and an IF gain control voltage for proper operation. The AD607 does have a maximum input RF power of -15 dBm; however, due to the inherently low signal nature of imaging small volumes at low-field strengths, this has not proved to be a limitation in the prototype system.

The audio filter/ sample-and-hold block contains both a 2-channel, low-pass audio filter and a 2-channel sample-and-hold amplifier. The audio filter serves as an anti-aliasing filter for the baseband digitizer. The audio filter is made up of two MSFS2P chips from Mixed Signal Integration. Each MSFS2P forms a single-chip, switched capacitor filter with an electronically tunable cutoff frequency from 0-20 kHz and an on-chip gain selectable between 0, 10, and 20 dB. The sample-and-hold circuit is based upon two Analog Devices AD781 chips, each of which has a 700 nsec acquisition time and an input bandwidth of 1 MHz. The sample-and-hold amplifier allows the signals on the I and Q channels to be simultaneously sampled prior to the digitizer in the computer control block. Thus, inexpensive digitizer cards, which often multiplex a single analog-to-digital converter between two input channels and consequently introduce time skew in the acquired MR signal, may be used to further reduce system cost.

System evaluation has been done by comparing images made with the desktop transceiver to those obtained from a commercial scanner (Varian SIS-85). Images were made using a 0.16 Tesla whole body IGC magnet. This magnet is used as a test platform due to the large working space. All images were obtained using the same gradient and RF coils and gradient amplifiers.

RESULTS

The completed prototype MR transceiver is shown in Figure 4. Images were obtained using a standard spin echo sequence (TE= 40 msec, TR= 1 sec, 1 average) on the 0.62-in. (16 mm) diameter distilled water and vegetable oil phantom in Figure 5. Magnitude images of the comparison data appear in Figures 6a (prototype system) and 6b (commercial system). Relative SNR was computed by taking the ratio of the average signal level to the average noise level in the images. In the image of Fig. 6a, the desktop transceiver has a relative SNR of ~19.7. In Fig. 6b, the Varian SIS system has a relative SNR of ~19.4. Thus, in this preliminary example, the desktop transceiver has demonstrated SNR comparable to a commercial system. A small d.c. artifact remains in the image obtained with the desktop transceiver.

FIGURE 4. Prototype desktop MR system transceiver.

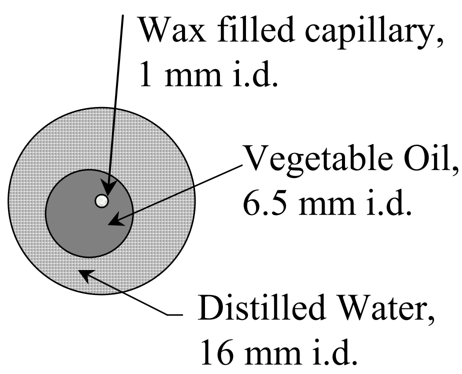
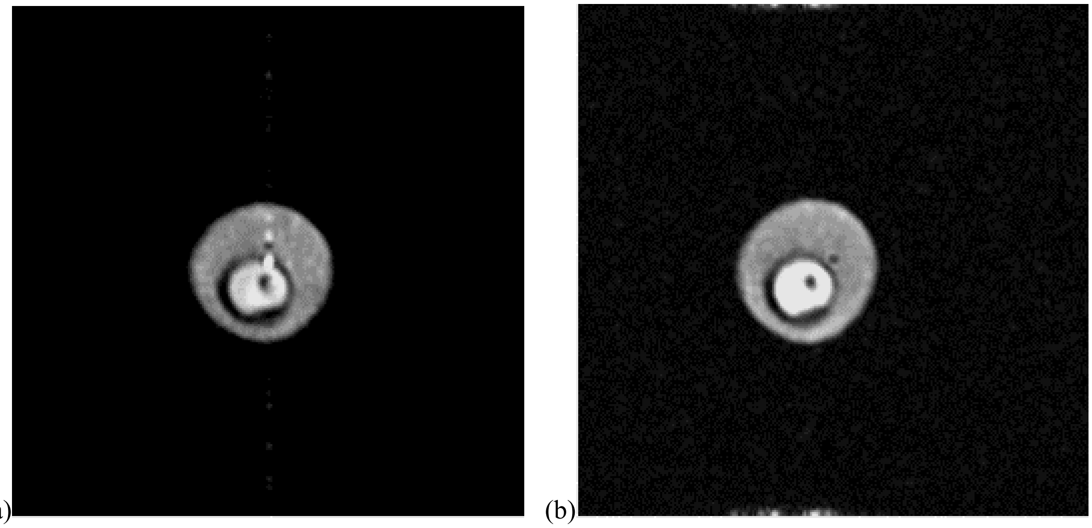


FIGURE 5. Imaging phantom used to compare SNR and image quality.



(a) (b)

FIGURE 6. (a.) Image from prototype desktop MR system transceiver. (b.) Image from Varian SIS-85 scanner.

DISCUSSION AND CONCLUSIONS

The low-cost desktop MR transceiver presented in this paper demonstrates SNR comparable to that available from a commercial MR scanner for spin-echo imaging of 1-in. phantoms at 0.16 Tesla. This instrument would be suitable for imaging small animals such as mice, and as a teaching tool. While not as stable and robust as a commercial scanner, this is significant in that the desktop transceiver, minus the computer control block, was constructed for less than $3,500 (the entire transceiver was built for under $10,000). These results demonstrate that MRI scanners with reasonable performance can be constructed at very low cost, which may make desktop MRI scanners a routine instrument in both research and educational laboratories.

At present, development of the prototype scanner continues. While preliminary results are promising, much remains to be done to fine-tune the system and increase its performance. Thus, modifications to expand system capability and lower system cost are ongoing.

ACKNOWLEDGMENTS

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