Implementation of low-cost, instructional tabletop MRI scanners

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PURPOSE: To build a set of 20 low-cost educational tabletop MRI scanners with 1cm FOV for an undergraduate engineering lab course with a budget of only $10K per system. While educational scanners are offered by a variety of vendors [1]-[3], none are available at this price point. Additionally, we intended to create an MRI scanner with an open parts list and library of pulse sequences which could be assembled, operated, and further improved by motivated students. This work builds on previous designs for educational systems [4] and open source relaxometers [5].

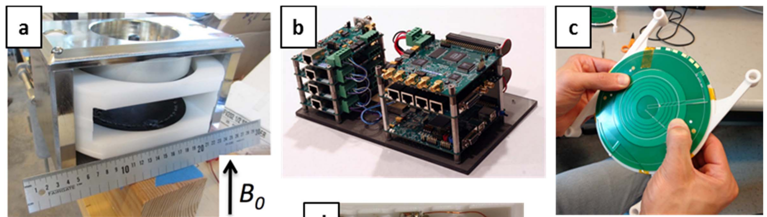
OUTLINE OF CONTENT:

System Components:

Magnet: A 0.19T B_0 field with ~50ppm homogeneity in 1cm DSV is created by two 15cm NdFeB disks held 4cm apart. An iron yoke confines the magnetic field to the gap between the pole pieces. Total weight is 13kg. (Fig. 1a)

Console: The MEDUSA console [6] is low cost and easy to program in MATLAB. It includes a controller board, RF TX/RX board, gradient waveform synthesizer, and digital-to-analog converter boards for each gradient axis. (Fig. 1b)

Gradients: Air-cooled shielded planar X, Y, Z, and Z2 gradient coils produce slopes of [13.7, 10.4, 12.3] mT/m/A for [x, y, z]. Coils are 8-layer boards (2 primary, 2 shielding) of 4 oz (140μm) copper and are positioned ±1 cm (primary) and ±2 cm (shielding) from isocenter. (Fig. 1c)



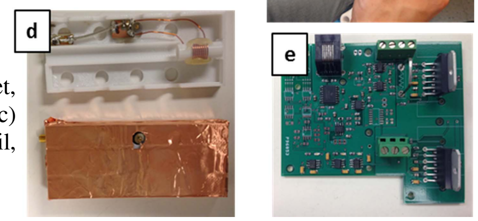


Figure 1: (a) NdFeB magnet, (b) MEDUSA console, (c) Gradient coil set, (d) RF coil, (e) Gradient power amplifier

RF Subsystem: A RF shielded solenoid coil is used for efficient RF transmission and reception (Fig. 1d). Samples are placed in a 10mm NMR tube and inserted into the solenoid. For RF transmit a Mini-Circuits 29.5 dBm amplifier is used. A PIN-diode activated quarter-wave T/R switch was built using a two-stage amplifier made of low-cost Mini-Circuits GALI-74+ ICs with 2.7dB noise figures in the receive path to achieve 50dB gain.

Gradient power amplifiers: Two OPA549 power op-amps are used in a bridged configuration to supply up to 6 amps of current to the gradient coil. A current sensor compares the output current to the input voltage to ensure that the current itself is proportional to the desired signal. (Fig. 1e)

GUIs: User interfaces written in MATLAB allow students to conduct experiments easily. Data can be saved for post-processing in MATLAB. Each GUI covers a topic such as free induction decay, flip angle calibration, and spin echoes. (Fig. 2)

Example Lab Excercises:

Projection imaging: A GUI is provided that runs a spin echo sequence, plots the Fourier transform (projection), and allows the user to turn on any of the gradient fields. The student inserts a "mystery phantom" which contains an unknown arrangement of 2mm capillary tubes. The student turns on 1 gradient axis and physically rotates the sample inside the RF coil while viewing the projection to deduce the capillary arrangement. (Fig. 2)

2D/3D imaging: GUIs are provided for 2D and 3D RARE sequences. 3D printed phantoms and biological samples (mouse brains and hearts) were imaged by students. (Fig. 3)

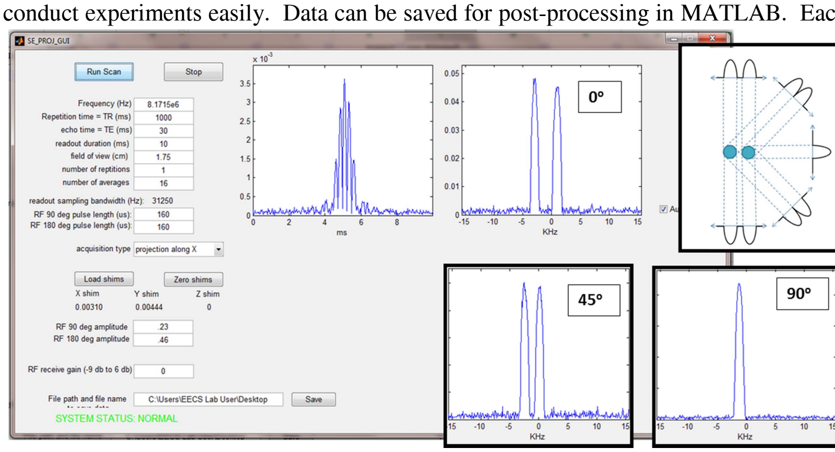


Figure 2: Spin-echo/Projection GUI, showing projections of rotated 2 tube phantom with x-gradient on. Cartoon of projection reconstruction also shown.

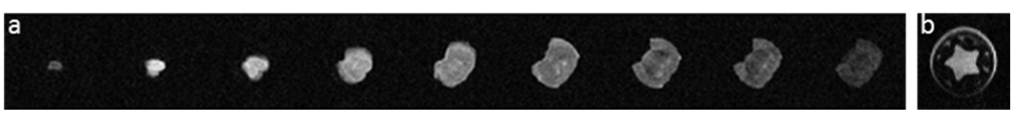


Figure 3: (a) Mouse brain acquired using 3D RARE (FOV = 1.75cm, 96 x 96 x 9 matrix). (b) Single-shot 2D image of start-shaped phantom (1.25 cm FOV, 96 x 96 matrix).

SUMMARY: A low-cost, open-interface classroom MRI scanner is demonstrated. The scanner was successfully used to interactively teach the concepts of free induction decay, flip angle measurement, B_0 shimming, gradient echo, spin echo, 1D projection, and 2D as well as 3D MR imaging. The system has sufficient SNR to acquire 2D images with ~175μm resolution in a single-shot spin echo train (no slice selection). A Wiki page has been published [7] to make the design publicly available as a "kit" and to encourage users to upload new pulse sequences and reconstruction codes. The Wiki page includes all of the parts lists, MATLAB GUIs, and circuit board Gerber files needed to build the scanner.

REFERENCES: [1] http://pure-devices.com/ [2] http://www.ebresearch.net/ [3] http://www.magritek.com/applications-teaching [4] Wright SM, MAGMA 2002. [5] Twieg M, ISMRM 2013 #0139. [6] Stang P, IEEE TMI 2011. [7] https://gate.nmr.mgh.harvard.edu/wiki/Tabletop_MRI

ACKNOWLEDGEMENTS: This work was a collaboration between the MGH Martinos Center for Biomedical Imaging, Stanford University, University of Freiburg, and the Chinese Academy of Sciences. Parts and equipment were funded by MIT for use in undergraduate course *6.S02 – Intro to EECS II from a Medical Technology Perspective*. Thanks to Simon Sigalovsky, Azma Mareyam, and Bo Zhu for their help.