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David J. Ariando · Soumyajit Mandal

Portable Low-Field MRI Scanners

Hardware, Imaging Methods, and Applications

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Dedicated to the memory of Prof. Richard R. Ernst (1933–2021), one of the inventors of Fourier transform NMR spectroscopy and imaging, a Nobel Laureate in Chemistry (1991), and an encouragement to us all.

Foreword

For the past decade, I have run a for-profit incubator (Weinberg Medical Physics) that has launched multiple medical imaging companies. Our spin-outs have included Promaxo and Tesoro Imaging, which market low-field MRI systems for urology and dental practices (respectively). For the past two years, we have been working on a new system for brain health, that will include both MRI and transcranial magnetic stimulation in a single compact system. In the process of that effort, our team has had the good fortune to collaborate with the authors of this book (Dr. Ariando and Dr. Mandal), who already had extensive experience in diverse compact magnetic resonance applications (including downhole scanners).

This timely book provides readers with an accessible and up-to-date introduction to the field of low-field magnetic resonance sensing and imaging, both highly dynamic areas of both research and commercial activity. It begins with a historical overview of MRI system design and a discussion of current developments. It goes on to analyze the underlying physics of MRI from a semi-classical perspective before describing the major hardware components of low-field scanners (including the magnet, coils, transmitters, receivers, gradient systems, and digital processors) in detail. Several examples of each component are described, thus helping readers to understand the major challenges and trade-offs involved in designing these complex devices. Finally, the book highlights the issues involved in integrating these components within a working system by presenting the architecture, design, and test results of several low-field MRI scanners (and non-imaging sensors, such as nuclear quadrupole devices) developed by the authors.

An important advantage of this book is that it emphasizes a system-level approach to the design of low-field MRI scanners. As someone who has personally been involved in the design of novel compact imaging systems for diagnosis and image-guided therapy, I can attest to the importance of such a system-level approach in solving the multi-domain challenges that arise within these devices. I expect the book to be valuable for both students and working engineers in this growing field.

Bethesda, MD, USA — Irving Weinberg
February 2024

Preface

Nuclear magnetic resonance (NMR) is a powerful spectroscopic technique that is widely used for studying the physical and molecular composition of complex samples. Advancements in NMR have led to the invention of magnetic resonance imaging (MRI), which is widely used in medical imaging due to its ability to create contrast in soft tissues. In addition, MRI has also been applied to studies of porous media (such as rocks), quality control for food products, inspection of polymers, the study of agricultural products, and many other applications.

Despite its diverse applications, the use of MRI is largely limited to large hospitals and academic or industrial laboratories. This can be mostly attributed to the fact that MRI scanners generally utilize large superconducting magnets or complicated permanent magnet geometries to generate strong and uniform magnetic fields. As a result, they are generally very expensive, require installation within special shielded rooms, and use extremely complex hardware and data acquisition methods.

Recent years have seen increasing interest in MRI scanners that avoid these disadvantages by using much weaker magnetic fields. Such "low-field" scanners are now commercially available from several sources, including startup companies. Some of these devices are even available in portable form factors, thus enabling point-of-care imaging in patient wards, doctor's offices, ambulances, and other scenarios. Others feature programmable magnetic fields that can be used for therapeutic purposes (such as delivering magnetic nanoparticles to tumors) in addition to imaging. However, the use of a weaker magnetic field is generally accompanied by a reduction in signal quality, while the need for portable form factors or programmable magnetic fields introduces significant challenges in hardware design, data acquisition, and signal processing. This book aims to provide a unified and accessible introduction to the unique advantages, challenges, and applications of such low-field MRI systems. It also discusses how these systems can be used for studying samples without explicitly generating images, for example, via relaxation or diffusion measurements. The book is organized into eleven chapters, as discussed below.

Chapter 1 provides a brief introduction to the history of nuclear magnetic resonance (NMR), which is the physical phenomenon utilized by magnetic resonance imaging (MRI) scanners. It also discusses the many applications of NMR and MRI, with a particular focus on those enabled by portable and low-cost devices.

Chapter 2 begins with an introduction to the theory of NMR, including the processes of signal generation, decay, and detection. It continues by describing common NMR measurement methods (known as pulse sequences) and the resulting precision (as quantified by the signal-to-noise ratio). Finally, it discusses the use of magnetic field gradients for spatial localization (which is the basis of MRI) and mechanisms for generating contrast in MRI images.

Chapter 3 provides a brief introduction to the design of magnets for portable low-field MRI systems. It begins by reviewing the state-of-the-art before describing two design examples. The first is an enclosed geometry based on a Halbach dipole array, while the second is a single-sided (open) geometry for a hand-held scanner.

Chapter 4 begins by describing the probe circuits that are commonly used in NMR measurements. The analysis shows the importance of probe dynamics for low-field NMR and MRI, where the probe bandwidth becomes comparable to or smaller than the measurement bandwidth. The results also provide the theoretical basis for the probe designs that are discussed in the book. Finally, this chapter discusses the design of RF coils and probe circuits for both enclosed and single-sided geometries.

Chapter 5 describes the development of high-bandwidth and high-power transmitters for tuned probes, which are common in low-field NMR. This effort is useful for portable NMR systems, especially low-cost systems like those described in this book, due to the gross inhomogeneity of the B_0 field generated by inexpensive magnets. In such fields, an increase in excitation bandwidth generally results in the excitation of a larger sample volume, which in turn improves the signal-to-noise ratio (SNR) of the measurement.

Chapter 6 describes the design of custom receivers for improving the noise figure (NF) of low-field NMR detection. Suitable design techniques for the receiver include the use of a differential high-input impedance pre-amplifier, capacitive feedback damping, frequency-tunable tuned load, and input damage protection.

Chapter 7 discusses both major components of the gradient systems required by low-field MRI systems, namely the gradient driver and the gradient coil. It begins with the design of portable pulsed field gradient drivers that are lightweight and battery-powered. A practical implementation of such a gradient driver is shown to be capable of generating at least 3 A of current over a duration of at least 2 ms, which is sufficient for many portable low-field NMR/MRI systems. Next, the chapter discusses the design of gradient coils for both enclosed and single-sided systems.

Chapter 8 discusses the design of digital controllers for low-field MRI systems. It begins by describing the data transport architecture of the digital processor, which typically includes both a field-programmable gate array (FPGA) and a system-on-chip (SoC). Additionally, it describes the concept of bitstream programming for defining pulse sequences within the FPGA. Finally, it discusses the various programming domains used by the system, as well as their unique roles.

Chapter 9 focuses on nuclear quadrupole resonance (NQR), which is a magnetic resonance technique closely related to NMR that is commonly used to characterize crystalline solids. Spatially-resolved NQR is of particular interest for studying the position, structure, and function of such solid samples. The chapter discusses a “single-shot” method for accelerating spatially-resolved NQR measurements (thus enabling the rapid generation of NQR images). This method utilizes the fact that certain NQR relaxation rates are field-dependent, which in turn allows measured relaxation time distributions measured in a static field gradient to be converted into spatial distributions.

Chapter 10 brings together many of the topics discussed in the previous chapters by discussing the design and operation of complete low-field MRI systems. Several examples are presented, including an autonomous low-field NMR console, a low-cost desktop MRI system for studying food products, a hand-held single-sided MRI sensor, and a complete low-cost portable MRI scanner.

Chapter 11 concludes the book. It begins with a brief summary of the work described in the earlier chapters. It then discusses various hardware improvements and signal processing techniques for further improving the performance of low-field MRI systems based on both single-sided and enclosed sensor geometries.

We hope that readers will come away from this book with enough knowledge to effectively study and appreciate the research literature. The text should be particularly useful to graduate students in Electrical Engineering, Computer Engineering, Biomedical Engineering, Physics, and related disciplines who are involved in research on low-field NMR and MRI. It may also be of interest to practicing engineers and scientists in the field, particularly those working in companies that are developing such imaging and therapeutic devices.

San Carlos, CA, USA David J. Ariando
Merrick, NY, USA Soumyajit Mandal
February 2024

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Contents

Acronyms

ABS	Acrylonitrile butadiene
ADC	Analog-to-Digital Converter
AMEX	Axis-Matched EXcitation
ANC	Active Noise Cancellation
ANN	Artificial Neural Network
ASIC	Application-Specific Integrated Circuit
AXI	Advanced eXtensible Interface
BRD	Butler-Reeds-Dawson
BSS	Blended Soy Sauce
CAD	Computer-Aided Design
CMCD	Current-Mode Class-D
CMRR	Common-Mode Rejection Ratio
CNC	Computer Numerical Control
CP	Carr-Purcell
CPMG	Carr-Purcell-Meiboom-Gill
CW	Continuous Wave
DAC	Digital-to-Analog Converter
DFT	Discrete Fourier Transform
DMA	Direct Memory Access
DOI	Depth of Investigation
DSP	Digital Signal Processing
dsv	Diameter of the sample volume
EFG	Electric Field Gradient
EMI	Electromagnetic Interference
FBP	Filtered Back-Projection
FDA	Food and Drug Administration
FDM	Fused Deposition Modeling
FET	Field-Effect Transistor
FFT	Fast Fourier Transform
FID	Free Induction Decay

FIFO	First-In First-Out
FOM	Figure of Merit
FOV	Field of View
FPGA	Field-Programmable Gate Array
FSM	Finite State Machine
FSS	Fermented Soy Sauce
GaNFET	Gallium Nitride Field-Effect Transistor
GPIO	General Purpose Input/Output
GRE	GRadient Echo
HDL	Hardware Description Language
IC	Integrated Circuit
IDFT	Inverse Discrete Fourier Transform
ILT	Inverse Laplace Transform
IoT	Internet of Things
IRSE	Inversion Recovery Spin Echo
kNN	*k*-Nearest Neighbors
LDO	Low Dropout Regulator
LNA	Low-Noise Amplifier
LVDS	Low-Voltage Differential Signaling
MCU	Microcontroller Unit
MEMS	Micro Electro-Mechanical System
MIR	Mid-infrared
ML	Machine Learning
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MRI	Magnetic Resonance Imaging
NF	Noise Figure
NIR	Near-infrared
NMR	Nuclear Magnetic Resonance
NQR	Nuclear Quadrupole Resonance
OCT	Optimal Control Theory
ODE	Ordinary Differential Equation
OS	Operating System
PA	Power Amplifier
PAP	Phase-Alternating Pair
PAS	Principal Axis System
PC	Personal Computer
PCA	Principal Components Analysis
PCB	Printed Circuit Board
PCMCD	Pulsed Current-Mode Class-D
PDE	Partial Differential Equation
PFG	Pulsed Field Gradient

PGA	Programmable Gain Amplifier
PGSE	Pulsed-Gradient Spin Echo
PLA	Polylactic acid
PLL	Phase-Locked Loop
PLS-DA	Partial Least-Squares Discriminant Analysis
POC	Point-of-care
PSD	Power Spectral Density
PSNR	Peak Signal-to-Noise Ratio
QA	Quality Assurance
RF	Radio Frequency
RFI	Radio Frequency Interference
RMSE	Root Mean Squared Error
SDRAM	Synchronous Dynamic Random Access Memory
SE	Spin Echo
SLSE	Spin-Locked Spin Echo
SNR	Signal-to-Noise Ratio
SoC	System-on-Chip
SoM	System-on-Module
SPA	Symmetric Phase-Alternating
SPI	Serial Peripheral Interface
SQUID	Superconducting Quantum Interference Device
SSIM	Structural SIMilarity
SVD	Singular-Value Decomposition
SVM	Support Vector Machine
TF	Transfer Function
VMCD	Voltage-Mode Class-D
ZCS	Zero Current Switching
ZVS	Zero Voltage Switching

1 Introduction

1.1 Historical Overview of NMR and MRI Systems

1.1.1 Background

Nuclear magnetic resonance (NMR) is a powerful spectroscopic technique that studies the dynamics of atomic nuclei in time-varying electromagnetic fields. NMR is widely used in the fields of physics and chemistry for studying the physical and molecular composition of complex samples. Advancements in NMR have led to the invention of magnetic resonance imaging (MRI), which is widely used in medical imaging due to its ability to create contrast in soft tissues. In addition, MRI has also been applied to studies of porous media (such as rocks), quality control for food products, inspection of polymers, the study of agricultural products, and many other applications. This book focuses on MRI systems for such non-clinical applications.

1.1.2 A Brief History of NMR

The basic concept of NMR is to detect magnetic dipole transitions between nuclear energy levels in the presence of an external magnetic field. As will be discussed in later chapters, such transitions occur at a specific resonance frequency, known as the *Larmor frequency*, which is proportional to the strength of the applied magnetic field. The possibility of detecting NMR transitions was originally proposed in the 1930s. The first experimental attempts were made by Dutch physicist Cornelius Gorter in 1936 using calorimetric methods, but with negative results [5]. A few years later, American physicist Isidor Isaac Rabi, working at Columbia University, demonstrated NMR phenomena for the first time by using radio frequency (RF) fields to induce transitions between the nuclear energy levels of a molecular beam. In 1938, Rabi's team observed the decrease in signal intensity of a lithium chloride (LiCl) beam at the

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detector under a resonance condition between the Larmor frequency of the sample (which was determined by the static magnetic field generated by a variable electromagnet) and fixed-frequency continuous-wave RF excitation produced by a hairpin coil. The significance of this result was recognized by the Nobel Prize in Physics, which was awarded to Rabi in 1944 for “his resonance method for recording the magnetic properties of atomic nuclei”.

In the early 1940s, research groups led by Felix Bloch [1] and Edward Purcell [10] independently discovered the principles of NMR spectroscopy and developed the first NMR spectrometers. At Harvard University, Purcell observed the resonance absorption peak of nuclear magnetic moments. Meanwhile, at Stanford University, Bloch demonstrated the voltage induced by a water sample when polarized with an oscillating magnetic field perpendicular to the static magnetic field, thus demonstrating the precessional motion of protons (^{1}H nuclei) expected during NMR experiments. Both Purcell and Bloch utilized continuous-wave (CW) measurement techniques. A few years later, American physicist Erwin Hahn, working at the University of Illinois, pioneered pulsed NMR techniques, including the generation of free induction decays (FIDs) and spin echoes [2]. Since then, pulsed NMR has become dominant due to its so-called multiplexing advantage, namely the ability to excite multiple resonant frequencies simultaneously in a single scan. The result is greatly increased measurement speed compared to CW techniques. Another advantage of pulsed NMR is the ability to combine multiple pulses with different properties (frequencies, amplitudes, and phases) into complex *pulse sequences* that provide a wide variety of measurement capabilities.

1.1.3 The Development of MRI

Since the early developments noted above, NMR has been utilized in numerous scientific disciplines, including chemistry, biology, physics, and material science. In the subsequent decades, NMR technology has continued to develop and improve, resulting in the invention of magnetic resonance imaging (MRI), which is now a common tool for the clinical diagnosis of living tissues. The widespread use of MRI in medicine can be attributed to several factors, including its non-invasive nature, its ability to image a wide variety of tissues, and its capacity to generate high-resolution two- or three-dimensional (2D or 3D) images that provide both anatomical and functional information.

MRI technology originated in the 1970s. American physician Raymond Damadian was the first to suggest that the distributions of NMR signal decay times (known as the *relaxation time constants* T_1 and T_2) differ between normal and cancerous tissues [3]. The first imaging method, namely back-projection using static magnetic field gradients, was proposed by American chemist Paul Lauterbur a few years later [8]. Lauterbur named the resulting images zeugmatograms, while the method itself was known as zeugmatography. The introduction of pulsed field gradients, together with use of the fast Fourier transform (FFT) for image reconstruction, greatly increased the speed of data acquisition compared to imaging methods based on back-projection. This approach, known as Fourier zeugmatography, was originally introduced by Swiss physicist Richard Ernst and his co-workers in 1975 [7]. Since then, the use of the FFT in NMR and MRI has become commonplace due to its computational efficiency. Soon afterwards, English physicist Sir Peter Mansfield used time-dependent magnetic field gradients to develop multi-planar imaging, which made 2D imaging practical by further speeding up image acquisition [9]. Finally, in 1978, the development of selective excitation methods [11] enabled 3D imaging and the first whole-body MRI scanners [6].

1.2 Summary of Current Developments

Despite the variety of potential applications, the use of MRI is mainly limited to large hospitals and academic or industrial laboratories. This can be largely attributed to the fact that MRI scanners generally utilize large superconducting magnets or complicated permanent magnet geometries to generate strong and uniform magnetic fields. As a result, they are typically very expensive (in the range of $800k–$5 million for the scanner and $3.25 to $15 per liter for liquid helium coolant), require installation within special shielded rooms, and use extremely complex hardware and data acquisition methods. Creating a more affordable class of devices would make MRI systems more accessible, thus providing the benefits of non-invasive biomedical imaging to less privileged segments of society.

Recent years have seen increasing interest in MRI scanners that reduce size and cost by using much weaker magnetic fields (less than 0.5 T). Such "low-field" scanners are now commercially available from several sources, including well-funded startups such as Hyperfine and Promaxo. However, the use of a weaker magnetic field is generally accompanied by a reduction in signal quality. In particular, the signal-to-noise ratio (SNR) of an NMR measurement increases approximately as $B_0^{7/4}$, where B_0 is the strength of the magnetic field. Thus, low-field systems suffer from low values of SNR, i.e., have intrinsically poor measurement precision. Nevertheless, some low-field MRI scanners are available in portable form factors, thus enabling point-of-care imaging in patient wards, doctor's offices, ambulances, and other scenarios. Other low-field scanners feature programmable magnetic fields that can be used for therapeutic purposes (such as delivering magnetic nanoparticles to tumors) in addition to imaging. Unfortunately, realizing these desirable features (portable form factors and programmable magnetic fields) introduces significant challenges in hardware design, data acquisition, and signal processing.

Another important challenge in low-field MRI is the decreasing sensitivity of conventional inductive detectors with resonant frequency (which is proportional to the field strength). Inductive detectors (also known as coils) detect the rate of change of sample magnetization over time. As a result, their sensitivity is proportional to the detection frequency. The authors in [4] provide a good introduction to ultra-low-field NMR and MRI using alternative detectors based on superconducting quantum interference devices (SQUIDs) or atomic magnetometers. The results are of great technical interest since these devices directly detect the sample magnetization (not its rate of change), and thus have better sensitivity than coils at low frequencies. However, the sensitivity of such detectors to static and low-frequency magnetic fields is a double-edged sword since it also makes them very susceptible to external interference. Important sources of interference include the Earth's magnetic field, AC power lines (at multiples of 50 or 60 Hz), and switching power converters. Reducing such interference to tolerable levels generally requires a significant amount of magnetic shielding. In addition, SQUIDs (but not atomic magnetometers) require cryogenic cooling; they are generally operated in liquid helium at 4K. Thus, ultra-low-field scanners using such detectors are generally operated within shielded rooms, i.e., are not particularly portable. As a result, most low-field NMR and MRI systems continue to use conventional inductive detectors (RF coils).

1.2.1 Applications of Low-Field MRI

Addressing and solving the challenges discussed above can improve current NMR and MRI systems and also lead to their adoption into new industries and scenarios. The use of low-field NMR is particularly useful for studying fluids inside porous media, such as sandstone and carbonate rocks, bones, and electrodes in electrochemical systems. The relaxation and diffusion spectra of fluids within such media are used to study molecular structure, distinguish between fluid types, and quantify key metrics such as porosity and permeability. For example, a key goal of fluid typing in sedimentary rocks is to distinguish between water and various types of hydrocarbons (crude oils and natural gas). Such *answer products* are important for optimizing the exploration and production strategy for oil and gas fields. Accordingly, the field of well-logging has pioneered many low-field NMR technologies for characterizing rocks and fluids (water, oil, and natural gas) deep underground [12–14].

Research in NMR well-logging and rock core analysis has also advanced the study of NMR physics and sample analysis [15–17]. In a porous medium, the relaxation of the NMR signal back to thermal equilibrium is driven by two main mechanisms, namely (1) bulk relaxation within the fluid [18], and (2) surface relaxation on the pore walls due to the presence of paramagnetic ions such as iron or manganese at grain boundaries [19]. The latter component increases for smaller pores due to their increased ratio of surface area, S, to volume, V. For example, a spherical pore has

$$\frac{S}{V} \propto \frac{1}{r}$$

where r is the radius. Thus, the observed relaxation spectrum of the fluid denoted by ($\rho(T_1)$ or $\rho(T_2)$) provides information on the pore size distribution, which in turn determines both the porosity and the permeability of the medium.

An increased static field, B_0, generates higher internal gradients within the porous medium due to local variations in magnetic susceptibility [20, 21]. Additional relaxation due to molecular diffusion within these gradients obscures variations in relaxation times with pore size, making it more difficult to determine porosity and permeability. It is possible to reduce relaxation due to internal gradients by using NMR pulse sequences that rapidly generate a series of spin echoes. Specifically, the sequence should ensure that $B_0 \times t_E$ is kept low (e.g., < 0.1 Gauss-second), where t_E is the time interval between successive echoes (also known as the *echo period*). However, the required value of t_E can become too short for the transceiver hardware as B_0 increases. For this reason, conducting such studies using high-field NMR is not ideal.

By contrast, longer values of t_E can be used at lower values of B_0, which relaxes the specifications of the transceiver. Consequently, low-field NMR (often at $B_0 \approx 0.05$ T) is (1) popular for characterizing liquid relaxation inside porous media, and (2) of great interest in the petroleum industry. Advancements in low-field NMR thus have the potential to enable new applications of magnetic resonance in the oil field and beyond. Making NMR and MRI devices (known as spectrometers or scanners, respectively) more portable and autonomous is one way to make progress in this area.

In modern usage, the term "portable" generally refers to something that can fit within a pocket and then taken and operated anywhere. The definition of portable NMR/MRI is slightly more convoluted due to the fact that conventional systems require large shielded rooms and cryogenic cooling in order to operate. There are many devices in the literature that do not require shielded rooms or cryogenic cooling and are thus labeled as portable. However, their form factors range from hand-held devices to systems that can be transported within vehicles [22–27]. From a pragmatic viewpoint, an NMR/MRI device can be considered portable if it can be easily moved from one location to another.

A common strategy for improving portability in biomedical imaging applications is to develop scanners for individual body parts, rather than the entire body. A number of research studies have been conducted on systems designed for imaging specific body parts, such as the lungs [28, 29], brain [23, 30–35], and elbow [36]. Other attempts along similar lines include small imaging systems for pediatrics [37] and low-cost full-body scanners [38].

In addition to its widespread use in medicine, low-field NMR has a great deal of potential for use in educational institutions [39] and various industries, such as the food industry [40–46]. Aside from being less expensive, low-field MR systems are also potentially small and lightweight, making them suitable for field applications. It is often unfeasible or impractical to transport samples in several applications, e.g., examinations of live stems or trees. These measurements were previously performed in controlled environments [47, 48], such as a laboratory or office, which occasionally caused destruction of the sample [49, 50]. Recent advances in MR technology, including low-field magnet design and miniaturized gradient amplifiers, have addressed this issue by enabling in-situ measurements. Modern magnet designs significantly reduce the total weight of MR systems. Examples include sparse Halbach arrays [51–54], low-field electromagnets [55], custom C-shaped magnets [56–59], and other custom geometries [60, 61]. Circuit design innovations, such as the use of high-efficiency switching amplifiers, have also significantly reduced the size and weight of the gradient amplifiers [62, 63]. The aforementioned research has enabled the construction of desktop-sized NMR systems that can image moderately-sized samples with diameters in the 1–20 cm range. For example, the benchtop research MRI system developed by Pure Devices (Rimpar, Germany) uses a 0.55 T Halbach-type permanent magnet and has a useful field of view (FOV) of 1 cm.

1.2.2 Autonomous Operation

One key assumption made in the references above, as well as many others, is that there will always be a trained operator and an external computer available for running the aforementioned systems. However, this is not always true in reality, which in turn places limitations on the operating envelope of the system. One specific example is in the context of well logging tools, which are often required to operate tens of thousands of feet below the earth's surface with a relatively low-bandwidth data link to the surface. Accordingly, recent work has focused on automating the parameter selection and measurement optimization processes for NMR well logging tools [65].

The advantages to having an automated system is obvious for well logging, but many other industries such as agriculture, in-line quality assurance, food, materials, and medicine can take advantage of NMR or MRI if such automated tools exist. A more in-depth discussion of such applications is included in Sect. 10.1. Briefly, a fully functional, autonomous, and portable NMR or MRI system usable in a variety of applications needs to be (1) low power, (2) portable, (3) low cost, and (4) automated in terms of data acquisition, signal processing, and decision making. The appropriate form factor of the system is application-specific, but should be as small as possible to meet the user requirements.

The general theme of this book is to describe both theoretical and experimental approaches to address the challenges described above, thus making low-field NMR/MRI systems more portable and accessible. The size and hardware complexity challenges are addressed by developing (1) simplified, optimized, and miniaturized magnets, and (2) modern technologies to miniaturize the electronics (both digital and analog) needed to drive an NMR/MRI system. The power requirements are addressed by (1) developing lower power hardware, and (2) utilizing numerically-optimized broadband pulses [66, 67] in inhomogeneous magnetic fields featuring large static gradients. The process of data acquisition is automated by developing algorithms for adapting measurement parameters to maximize user-selected metrics such as the signal to noise ratio (SNR) per unit time. Such algorithms can also enable autonomous operation of the proposed MR systems in situations where manual operation is not feasible or when continuous operation is needed. Finally, we describe the use of modern machine learning (ML) techniques for quantification and/or classification of sample properties. These automation steps help to eliminate the need for a trained operator to collect and analyze the NMR data, thus paving the way for MR systems to become consumer devices suitable for use by the general public.

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