ADI's Magnetic Resonance Imaging (MRI) Solutions

MRI System Theory and Typical Architecture

Magnetic resonance imaging is a non-invasive imaging technology to generate anatomical and functional images of the human body with no ionizing radiation. MRI generates images with excellent soft tissue contrast and, thus, is particularly useful for neurological, musculoskeletal, cardiovascular, and oncological imaging. The signals are detected from hydrogen nuclei in water or fat molecules, and the signal acquisition is based on the phenomenon of nuclear magnetic resonance, which deals with the interactions between nuclear spin and magnetic fields. The signal localization is achieved by the application of linear gradients of a magnetic field.

The generation of MRI images is a result of the sophisticated interaction between magnet, gradient system, and radio frequency (RF) system that interface with a computer system for communication between the different electronics. Gradient coils are used for localization of the MRI signal in three dimensions (x, y, and z). They are operated via a high power amplifier, which is controlled by the gradient control module. The RF system serves two main purposes. Transmitting the RF energy to the tissues to be imaged is one of the purposes, and the other is receiving the RF signal that is induced by the tissues in response to the transmitted energy. The RF transmitter contains four main components: a frequency synthesizer (DAC or DDS), the optional digital envelope of RF frequencies (mixer), a high power amplifier, and an RF coil. The RF receiver contains an RF coil, a preamplifier (LNA), the optional demodulator (mixer), bandpass filter, further amplification (VGA), and analog-to-digital converter (ADC).

MRI System Design Considerations and Major Challenges

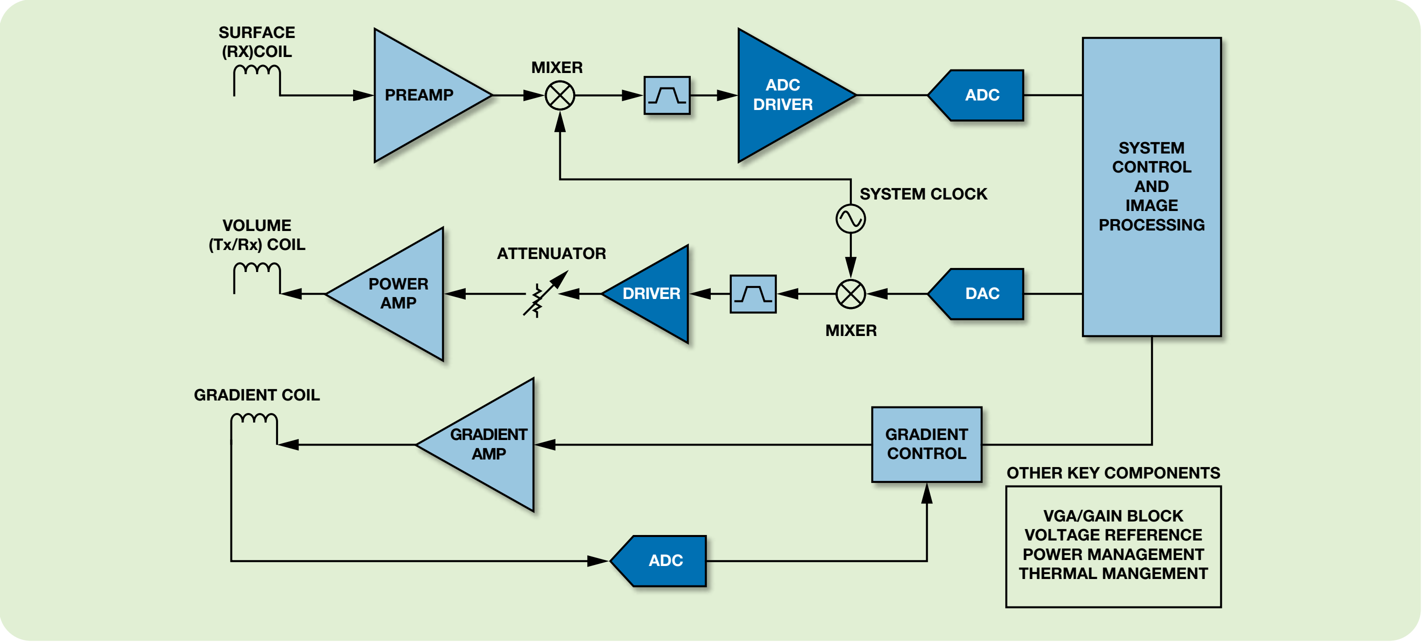
- Low noise performance is always the first consideration in MRI system design. The RF transmit path (Tx), RF receive path (Rx), and gradient control path all need a very low noise floor, so low noise amplifiers, higher resolution DAC and ADC, and low phase noise clocking must be selected in all the signal chains of an MRI system. From the system view, the dynamic range should be larger than 90 dB; the distortion should be better than –40 dBc; and total receiver noise figure should be less than 1 dB or closer to 0.5 dB. In order to get such system performance, the LNA noise figure should be less than 0.5 dB typically, 16-bit ADC is required for Rx, and 16-bit Tx DAC is required for Tx. High resolution should be taken into consideration during signal chain and power design, especially for laboratory instruments.
- The fast response time (a few microseconds) and very precise control are important for the gradient control. As the gradient amplifier current can be as high as 1000 A and must be controlled with 1 mA, which is on the order of 1 ppm, so the precision DAC is required for the analog gradient control and a very precise ADC (about 21 ENOB) is required by digital gradient control.
- The primary consideration in magnet quality is the homogeneity or uniformity. A typical MRI system must have less than 10 ppm variation over the imaging area. To prevent the image distortions caused by inhomogeneity, many MRI systems use a coil known as a shim coil to correct for them.

In traditional MRI systems is, the receive (Rx) electronics are located outside the room, the low level analog signals are sent to Rx electronics from the coil assembly over long coax, which is susceptible to interference. Recently, advances in high speed and resolution ADCs that are small size, low power consumption in non-magnetic packages have allowed system designers to migrate more channels of Rx electronics inside the room over fiber links, which provides lower interference, fast scans, and improved image quality for the system.

Total Solutions from ADI

ADI provides an extensive selection of amplifier, data conversion, signal processing, and power management solutions to maximize image quality and reduce power consumption and cost for MRI equipment. In addition, ADI provides evaluation boards, simulation tools, and applications expertise to support customer design and development efforts.

Main Signal Chain



Notes: The signal chains above are representative of an MRI system. The technical requirements of the blocks vary, but the products listed in the table are representative of ADI's solutions that meet some of those requirements.

Mixer	VGA	Gain Block	ADC Driver	ADC (Rx)	ADC (Gradient)	Amplifier
ADL5801/ADL5350/ AD8342/AD8343	AD8367/AD8366/ ADL5201/ADL5202	ADL5535/ADL5536	ADL5562/ADA4937-1/ ADA4938-1/AD8352	AD9653/AD9650/ AD9446/AD6655/ AD6649/AD9461	AD7760	AD8675/ AD8676

DAC (Tx)	DAC (Gradient)	Clocking	PLL	Temperature Sensor	Switch	Voltage Reference	Power
AD9142/AD9122/ AD9957/AD9788	AD5791/AD5781	AD952x/AD951x/ ADCLK8xx/ADCLK9xx	ADF4002/ADF4351/ ADF4350/ADF4360-8	ADT7310/ADT7410/ ADT7320/ADT7420	ADG9xx	ADR44x/ADR43x/ ADR42x	ADP2116/ADP2114/ ADP2386/ADP2384/ ADP7102/ADP7104/ ADP150/ADP151

Introduction of Main Products for MRI

Part	Description	Benefits
Mixer		
ADL5801	High IP3 active mixer with +27 dBm input IP3, +12.5 dBm input P1 dB, +1.5 dB power gain, and 9.75 dB SSB noise figure	Wideband RF, LO, and IF ports, single-channel up/ down converter
AD8342	LF to 3 GHz active receive mixer with +22.7 dBm input IP3, +8.3 dBm input P1dB, 3.7 dB conversion gain, and 12.2 dB noise figure, 0 dBm LO drive	Wide bandwidth and low intermodulation distortion and noise figure
VGA		
ADL5201	31.5 dB range programmable IF VGA. –11.5 dB to 20 dB gain range with 0.5 dB step, 7.5 dB noise figure at maximum gain, OIP3 > 50 dBm at 200 MHz, –3 dB bandwidth of 700 MHz, dual channel version: ADL5202	Wide input dynamic range, highp erformance power mode with power down control
AD8367	500 MHz, linear-in-dB VGA with AGC detector. Analog variable gain: –2.5 dB to +42.5 dB scaled 20 mV/dB	Gain up/down modes, with on-chip, square-law detector
AD8366	DC to 600 MHz, dual digital VGA. Gain range: 4.5 dB to 20.25 dB with 0.25 dB step. 11.4 dB @ 10 MHz at maximum gain and 18 dB at minimum gain, HD2/HD3 >90 dBc for 2 V p-p output at 10 MHz at maximum gain, OIP3: 45 dBm @ 10 MHz	Low noise and low distortion, excellent spurious-free dynamic range, suitable for driving high resolution ADC

Introduction of Main Products for MRI (Continued)

Part	Description	Benefits
Gain Block		
ADL5535	20 MHz to 1.0 GHz IF gain block with fixed gain of 16 dB. OIP3: 45.5 dBm @ 190 MHz 45.5 dBm @ 380 MHz, noise figure: 3.2 dB @ 190 MHz, 3.3 dB @ 380 MHz P1 dB of 18.9 dBm @ 190 MHz. Pin compatible with 20 dB gain version: ADL5536	Wideband, input/output internally matched to 50 Ω and integrated bias control circuit
ADC Driver		
ADL5562	3.3 GHz ultralow distortion RF/IF differential amplifier. V_N RTI: 2.1 nV/√Hz @ 12 dB gain. HD2/HD3: –91 dBc/–98 dBc @ 10 MHz, –102 dBc/–90 dBc @ 70 MHz, –104 dBc/–87 dBc @ 140 MHz, –80 dBc/–94 dBc @ 250 MHz, IMD3s of –94 dBc @ 250 MHz center	Wideband, low noise, low distortion issuitable for differential ADC driver
ADA4937-1	1.9 GHz ultralow distortion differential ADC driver. V_N RTI: 2.2 nV/√Hz. HD2/HD3: –112 dBc/–102 dBc @ 10 MHz, –84 dBc/–91 dBc @ 70 MHz, –77 dBc/–84 dBc @ 100 MHz	Drives the highest performance highspeed ADCs with CM adjust
ADC		
AD9653	Quad, 16-bit, 125 MSPS, serial LVDS 1.8 V ADC. SNR = 77.5 dBFS @ 70 MHz (2.6 V p-p input span), SFDR = 90 dBc (to Nyquist), 650 MHz full power analog bandwidth	Low power, small size with non-magnetic package suitable for MRI application
AD9650	Dual 16-bit, 25 MSPS/65 MSPS/80 MSPS/105 MSPS, 1.8 V ADC. SNR = 80 dBFS @ 70 MHz input and 105 MSPS data rate. SFDR = 92 dBc @ 70 MHz input and 105 MSPS data rate	On-chip dither option for improved SFDR, differential input maintains excellent SNR
AD9446	16-bit, 80 MSPS/100 MSPS ADC. SNR = 83.6 dBFS @ 30 MHz input (3.8 V p-p input, 80 MSPS) SNR = 82.6 dBFS @ 30 MHz input (3.2 V p-p input, 80 MSPS) SFDR = 89 dBc@ 30 MHz input (3.2 V p-p input, 80 MSPS)	Outstanding SNR, on-chip reference and high input impedance T/H with adjustable analog input range for MRI application
AD9258	Dual, 14-bit, 80 MSPS/105 MSPS/125 MSPS, 1.8 V ADC. SNR = 77.6 dBFS @ 70 MHz input and 125 MSPS data rate. SFDR = 88 dBc @ 70 MHz input and 105 MSPS data rate	High performance, combined with low cost, small size, can be used in low end MRI systems
AD7760	24-bit 2.5 MSPS, sigma-delta ADC. SNR: 120 dB @ 78 kHz output data rate, 100 dB @ 2.5 MHz output data rate	On-chip buffer/amplifiers simplify design, easy to be used in MRI gradient control
Amplifiers		
AD8676	Precision operational amplifier. Low voltage noise: 2.8 nV/√Hz, low offset: 12 μV typ, low input bias current: 2 nA max, voltage offset drift: 0.6 μV/°C max	Suitable for output buffer for dc precision and reference buffers
DAC		
AD9142	Dual, 16-bit, 1.6 GSPS DAC. Flexible LVDS interface, integrated 2×/4×/8× interpolator. Very small inherent latency variation: <2 DAC clock cycles	Advanced low spurious and distortion provide high quality, lower power
AD9122	Dual, 16-bit, 1.2 GSPS DAC. Flexible LVDS interface, integrated 2×/4×/8× interpolator. Adjustable analog output from 8.7 mA to 31.7 mA	Gain, dc offset, and phase adjustment for sideband suppression
AD9957	1 GSPS quad digital upconverter with 18-bit I/Q data path and 14-bit DAC. 250 MSPS input data rate, phase noise ≤ –125 dBc/Hz (400 MHz carrier @ 1 kHz offset)	Excellent dynamic performance, integration reduces complexity
AD5791	1 ppm/°C, 20-bit, ±1 LSB INL, voltage output DAC. Low 7.5 nV/√Hz noise spectral density and low 0.05 ppm/°C temperature drift. 1 μs settling time	Simplifies the design, lowers cost and reduces risk for MRI gradient control
Switch		
ADG901	4.5 GHz bandwidth, 40 dB isolation at 1 GHz, CMOS 1.65 V to 2.75 V, SPST switches. Low insertion loss: 0.8 dB @ 1 GHz	Wideband, full family with SPST, SPDT, 4:1 and 2 × SPDT
Voltage Reference		
ADR43x	Ultralow noise voltage references with current sink and source; 0.15% accuracy and 10 ppm/°C for A grade	Low drift and high accuracy benefit ADC sampling performance
Clocking		
ADCLK8xx/ ADCLK9xx	Multi-output fanout buffer optimized for low jitter and low power operation. Additive broadband jitter less than 500 fs	Well suited for low jitter MRI clock distribution
AD951x/ AD952x	Multi-output clock distribution functions with sub picosecond jitter performance, along with an on-chip PLL and VCO	Well suited for low jitter MRI clock divide and distribution
PLL		
ADF4002	Phase detector/frequency synthesizer with 5 MHz to 400 MHz bandwidth, 104 MHz phase detector. Normalized phase noise: –222 dBc/Hz	Programmable charge pump currents, very good phase noise performance
ADF4351	Wideband synthesizer with integrated VCO. 35 MHz to 4.4 GHz output frequency range, typical jitter: 0.3 ps rms, typical EVM at 2.1 GHz: 0.4%	Low phase noise VCO, programmable dual-modulus prescaler
Temperature Sensor		
ADT7420	Digital I^2C temperature sensor with ±0.25°C accuracy from –20°C to 105°C, 16-bit resolution (0.0078°C), ADT7320 is the SPI interface version	No calibration required, over/undertemperature interrupt
ADT7410	Digital I^2C temperature sensor with ±0.5°C accuracy from –20°C to 105°C, 16-bit resolution (0.0078°C), ADT7310 is the SPI interface version	No calibration required, over/undertemperature interrupt

Introduction of Main Products for MRI (Continued)

Part	Description	Benefits
Power Management		
ADP2114	2.75 V to 5.5 V input, configurable, dual 2 A/single 4 A, synchronous step-down dc-to-dc regulator. pin-pin compatible with dual 3 A version: ADP2116	Synchronous, optimized gate drive slew rate to support noise sensitive ADC/DAC
ADP2384	4.5 V to 20 V input, 4 A output current, synchronous step-down dc-to-dc regulator. Pin-pin compatible with 6 A version: ADP2386	High efficiency, accurate current limit allow the use of smaller inductor
ADP7102	3.3 V to 20 V input, 300 mA output current, 200 mV low dropout voltage LDO with low noise performance, 15 μV rms for fixed voltageoutput, high PSRR 60 dB at 10 kHz, reverse currentprotection. Pin-pin compatible with 500 mA version: ADP7104	Improves performance of noise sensitive loads and low dropout
ADP150	2.2 V to 5.5 V input, 150 mA output current, 105 mV low dropout voltage LDO withlow noise performance, 9 μV rms independent voltage output, high PSRR 70 dB at 10 kHz. Pin-pin compatible with 200 mA version: ADP151	Improves performance of noise sensitive loads and low dropout
ADP5052	4.5 V to 15 V input, channel-1, channel-2: programmable 1.2 A/2.5 A/4 A sync buck regulators with low-side FET driver; channel-3, channel-4: 1.2 A sync buck regulators; channel-5: 200 mA low dropout LDO	5-channel integrated power solution provides reduce the design difficulty and also the board size

Design Resources

Reference Circuits

- Very Low Jitter Encode Sampling Clock for High Speed ADCs Using the ADF4002 PLL (CN0003)—*www.analog.com/CN0003*
- Using the AD8352 as an Ultralow Distortion Differential RF/IF Front End for High Speed ADCs (CN0046)—*www.analog.com/CN0046*
- Interfacing the ADL5534 Dual IF Gain Block To The AD9640 High Speed ADC (CN0049)—*www.analog.com/CN0049*
- Powering a Fractional-N Voltage Controlled Oscillator (VCO) with Low Noise LDO Regulators for Reduced Phase Noise (CN0147)—*www.analog.com/CN0147*
- Interfacing the ADL5375 I/Q Modulator to the 9122 Dual-Channel, 1.2 GSPS High Speed DAC (CN0205)—*www.analog.com/CN0205*

Application Notes/Articles

- How ADIsimADC Models an ADC (AN-737)—*www.analog.com/AN-737*
- Sampled Systems and the Effects of Clock Phase Noise and Jitter (AN-756)—*www.analog.com/AN-756*

Design Tools/Forums

- ADC
  - High speed ADC evaluation board with schematic and PCB layout gerber file
  - High speed FPGA-based data capture board (HSC-ADC-EVALCZ)—*www.analog.com/fifo*
  - VisualAnalog™ software—*www.analog.com/VisualAnalog*
  - ADC SPI interface software (SPIController)
  - ADIsimADC modeling tool—*www.analog.com/ADIsimADC*
- Clocking and PLL
  - ADIsimCLK modeling tool—*www.analog.com/ADIsimCLK*
  - ADIsimPLL™: PLL design and simulation—*www.analog.com/ADIsimPLL*
  - AD951x/AD952x evaluation software and board
- Amplifier
  - ADIsimOpAmp: amplifier parametric evaluation tool—*www.analog.com/ADIsimOpAmp*
  - DiffAmpCalc™: differential amplifier calculator—*www.analog.com/diffampcalc*
- PMP
  - ADIsimPower™: power design tools—*www.analog.com/ADIsimPower*
  - Evaluation board

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