Choosing High-Speed Signal Processing Components for Ultrasound Systems

by Paul Errico and Allen Hill

Medical ultrasound requires the control and processing of a variety of high-speed signals. Those signals include high-frequency sound waves, high-frequency/wide-dynamic-range continuous/pulsed waves, high-speed digital processing and video displays. The challenge facing many circuit designers is to combine all those high frequency signals while facing severe constraints on power consumption, circuit-board area and cost.

Ultrasound research, development, and commercialization have sprouted in the last four decades. It wasn't until the late '60s that the first commercial ultrasound scanner became available for cardiology, neurology and ob/gyn applications. The next major breakthrough came with the introduction of gray-scale imaging, followed by real-time gray scale scanning. Another major advancement was introduction of color Doppler, which is used to determine the velocity and direction of blood flow.

An ultrasound instrument for imaging interior portions of the human body is a sophisticated system; it comprises many high-speed processing elements and subsystems. The underlying concept behind ultrasound imaging is similar to that of sonar. A sound wave is transmitted from a transducer or transducer array, which also "listens" for the reflected signal (Figure 1). By using signal processing techniques to combine the reflected signals, and performing this process over a wide scan area, an image can be constructed to profile the area. Unlike sonar, ultrasound operates at high frequencies (1 to 10 MHz), penetrates to depths of many centimeters inside the human body, and can be used to create 1-, 2-, and 3-dimensional images.

Market Technology Hurdles and High Speed Products

Unlike other diagnostic imaging modalities, ultrasound offers real-time video and audio outputs unachievable with other imaging techniques. To the trained eye and ear, video displays and audio signals offer important diagnostic information.

The system frame rate and spatial resolution, and the gray-scale or color-video display parameters, establish the boundaries for the rate at which signals must be transmitted, received and processed. A rule-of-thumb is that sound waves travel at 1540 m/s in soft tissue. For example, an ultrasound signal that has to travel a total of 20 cm (10 cm into the body and 10 cm return) will take approximately 130 µs. The total time required to generate 128 scan lines (a typical number for a "fan" type of display) would be 130 µs × 128 = 16 ms, for a maximum update rate of 60 frames per second (fps). Also, if each scan line has multiple focal zones, the components used for transmitting and receiving must have fast slew rates, settling times, and conversion rates.

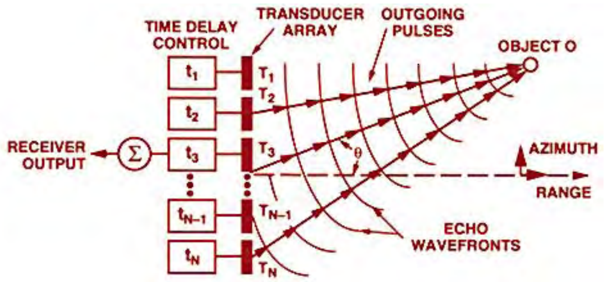

Figure 1. Transducer phased array for ultrasonic scanning.

A rule-of-thumb for attenuation of ultrasound signals in soft tissue is 1 dB/cm/MHz. For example, a 5-MHz signal will have an attenuation factor of 5 dB/cm. If the target is at a depth of 10 cm, the reflected signal will be attenuated by 100 dB. This suggests that frequencies lower than 5 MHz are usually used when imaging deeper into the body.

Another important feature of an ultrasound system is that it must be portable, yet operate under power supplied by a standard 120 V/ 220 V outlet. So low power is a critical requirement for all the high speed signal processing components. Low power per-channel becomes especially critical as the number of Transmit and Receive channels increases.

These "hurdles" illustrates the need for high speed, low distortion, wide dynamic range and low power signal chain components.

Market Trends

Analog beam-forming (ABF) ultrasound systems have multiple analog front end (AFE) channels (See Figure 2). The variable-gain amplifier is needed to compensate for attenuation in the medium being penetrated. The time delay element is used to maximize the signal-to-noise ratio of the reflected signal from a predetermined point source (focal zone). Corresponding points on the time-delayed signals from each channel are summed, compressed and amplitude detected (rectified). Analog-to-digital

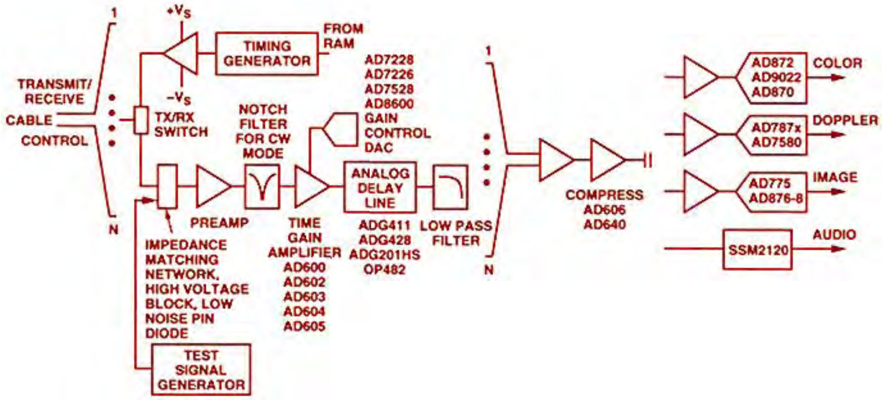

Figure 2. Front-end signal electronics for analog beam-forming system.

converters (ADCs) process *image* (8-10 bits, 20 MHz), *audio* (baseband 12 and more bits at audio sample rates) and color *Doppler* information (up to 12 bits at up to 10 MHz).

Digital data is processed with the use of FPGA, fixed-function off-the-shelf digital components, and digital signal processors (DSPs). The real-time capability of ultrasound requires optimization by digital processing (which includes FIR, IIR filters and FFT processing). The digitized data—in polar coordinates—must then be processed and mapped into rectangular coordinates, stored in buffer memory, and sent to the video and audio encoders.

Digital beam forming (DBF) systems replace the time delay element per channel with an ADC per channel and storage of successive signal elements in buffer memory (See Figure 3). The converter will typically be clocked at 40 MHz and will require 10-bits of resolution.

HIGH-SPEED IC COMPONENTS FOR ULTRASOUND*

Switching: In ABF systems high-speed multiplexers are used to create a cross-point switch. The switch is used to choose a predetermined time delay per channel by connecting each receive channel to a lumped passive LC element or active circuit element. Multiplexers must exhibit low R_{on} and fast T_{on}/T_{off} switching characteristics. Switch settling times >100+ ns are not fast enough for multiple measurement points (gates) during a single scan line. Quad high speed switches like the ADG201HS, ADG411 and ADG441/2/4 offer fast T_{on}/T_{off} switching speeds.

	T_{on} max	T_{off} max	Faxcode*
ADG210HS	50 ns	50 ns	1493
ADG411	175 ns	145 ns	1503
ADG441/2/4	110 ns	60 ns	1513/4/5

Time gain-control: The time-dependent variable-gain, or time-gain-control (TGC), amplifiers are critical receiver components for both ABF and DBF architectures. Since the magnitude of the reflected ultrasound signal depends on the depth of penetration and is much greater close to the receiver, the gain must be increased as time increases. The 1 dB/cm/MHz rule-of-thumb attenuation figure requires that the TGC gain must be a linear function of the control voltage or "linear in dB". Also, the bandwidth, group delay and distortion should be independent of the gain. Three first-generation wide-bandwidth (up to 90 MHz), low-noise (<1.7 $nV/\sqrt{Hz}$), low-distortion TGC amplifiers have been available for this function. The second generation types, (AD604 and AD605) available in sample quantities, offer wider gain control, increased integration, lower power and cost.

	Channels	Input Voltage Noise $nV/\sqrt{Hz}$	Gain Range	Faxcode*
AD600	2	1.2	0 dB to +40 dB	1193
AD602	2	1.22	−10 dB to +30 dB	1194
AD603	1	1.5	Programmable from −11 dB to +51 dB with 40-dB gain range	1195
AD604	2	0.75	Programmable 14-20 dB preamp, 0 to +48 dB, +6 to +54 dB	Call ADI Sales
AD605	2	1.7	Single-supply, 48-dB gain range Programmable −14 dB to +48 dB	Call ADI Sales

The TGC control DAC provides the voltage controlling the TGC gain with 8-bit resolution. Its output slew rate and settling time must be fast enough to perform the "linear in dB" voltage control. The data must be loaded fast enough to update each control DAC for each new measurement point. Since multiple receiver channels are used in both ABF and DBF, multichannel DACs such as the AD8600, AD7228 and AD7528 are desirable.

	Channels	Slew Rate (min)	Data Setup (min)	Faxcode*
AD8600	16 (V-Out)	4 V/µs	40 ns	1429
AD7228A	8 (V-Out)	2 V/µs	90 ns	1261
AD7528	2 (I-Out)		130 ns	1298

Amplifiers: Throughout the system, analog signals need to be buffered, scaled, amplified and filtered. High speed buffers are used to drive analog to digital converters or used to drive high speed signals over long or short lengths of cables (e.g., from the system to the transducer head). They are also used to drive signals from one pc board to another through connectors or along the etches of a pc board.

Compression and detection of high-frequency signals is used to boost the effective range of the converter and to improve system performance. The AD606 and AD640 are two wideband logarithmic amplifiers which provide the necessary compression and have the signal bandwidth required for analog beam forming ultrasound. The AD606 provides 80 dB of dynamic range with frequencies up to 50 MHz; the AD640 offers 50 dB of dynamic range up to 120 MHz, and two devices can be cascaded for 95 dB. In some modes of operation the compressed output will overrange and saturate the next component in the signal chain. Wideband clamp amplifiers like the AD8036/8037 are ideal buffers for this application; they can also be used to limit the analog input voltage and to drive high speed ADCs, preventing the analog input from saturating the ADC input sample-and-hold.

Besides having wide bandwidth and economy of power, amplifiers used in the receiver signal chain (many per system) must also have low distortion. Amplifiers like the AD8011, AD8001, AD8047

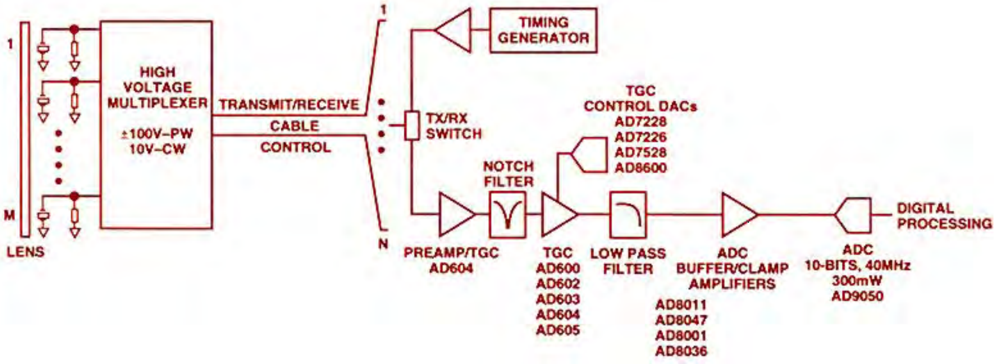

Figure 3. Front end signal electronics for digital beam system.

***For data on these products, call ADI's AnalogFax™ line, 1-800-446-6212, and enter the appropriate Faxcodes.**

and AD9631/32 offer the speed and performance required in many ultrasound applications.

High speed video amplifiers are also used for driving cables to monitors and video capture devices. Video amplifiers like the AD817/AD818 and AD826 and AD828 offer good video performance, such as differential phase and gain specs.

	Principal Function	Faxcode*
AD8001	800 MHz, 50 mW	1396
AD8011	300 MHz, 1 mA	1863
AD8047/48	250 MHz, general purpose	1868
AD9631/32	High-speed, low distortion	1468
AD8036/37	Wideband, clamp	1836
AD812	Dual 65-MHz, 40 mW	1402
AD817/818	Video	1404/05
AD813	Triple video amp, power down	1403
AD826/828	Video, 2-channel AD817/AD818	1408/10

A/D converters: The ongoing shift to DBF is increasing the number of ADCs used per system. As lower-power, lower-cost, and higher-performance ADCs become available, ultrasound designers are incorporating a single ADC for each transducer element. This allows beam forming to be accomplished in the digital domain, which offers inherent stability and increased accuracy. DBF eliminates the bulky LC delay elements and replaces each with a high speed ADC. The typical number of channels per system ranges from 64 up to 256, determined by the number of transducer elements and signal-to-noise ratio target.

The AD9050 (10-bit, 40-MSPS ADC) is designed to meet the demanding requirements of DBF ultrasound systems. First in importance is low power. With up to 256 ADCs per system, even small increases in ADC power significantly increase overall system power. The AD9050 uses only 300 mW operating from a single supply (+5 V); it utilizes an innovative architecture and is fabricated on a state-of-the-art BiCMOS process.

ADC performance is critical for image quality. The key requirement of the DBF system designer is to provide the best quality image at the lowest power and cost. The key ADC parameter used to quantify image quality is effective number of bits (ENOBs). The closer the ADC's ENOBs are to theoretical resolution, the more faithful the image reproduction. The image bandwidth is determined by the transducer frequency, which typically ranges from 1 to 10 MHz. The ADC's ENOB vs. frequency plot should be flat over the bandwidth of interest.

The sample rate for the ADC is chosen judiciously for optimal system performance. High clock rates provide the ability to resolve small time delays, which improves focus in the digital beam former. High clock rates also allow 4× oversampling of the transducer frequency to permit efficient detection for color flow applications. Most DBF systems operate with clock rates in the range of 30 to 40 MSPS. The AD9050 samples up to 40 MSPS, and its clock input and digital outputs can be configured for 5-V or 3-V operation. The use of 3-V ASICs to process the ADC's digital output is becoming increasingly common as designers seek to minimize system power.

Another key ADC parameter for ultrasound systems is recovery time from input overdrive. In Doppler modes, gain is set to the maximum because the measured phenomenon is very small (blood velocity). In this case, the reflected signal from a vessel wall will overdrive the ADC input; then upon recovery valid measurements of blood flow are made. With only 10 bits of ADC resolution, multiple data records must be averaged to achieve accurate blood flow measurements. If overdrive recovery is not consistent then lack of correlation between records will cause flow measurement errors.

The analog input section of the AD9050 is designed to prevent damage and corruption of data when the input is overdriven. The nominal input range is +2.8 V to +3.8 V (1 V p-p, centered at 3.3 V). "Out-of-range" comparators detect when the analog input signal is beyond this range and shut off the input track-hold. The digital outputs are locked at their maximum or minimum value (i.e., all "0" or all "1"). This prevents them from changing to an invalid value when the analog input is out of range. The input is protected for up to 0.7 V beyond the power supply rails; i.e., for nominal power (+5 V and ground), the analog input will not be damaged with signals from +5.7 V to –0.7 V.

When the analog input signal returns to the nominal range, the out-of-range comparators switch the track-hold back to the active mode and the device recovers in approximately 10 ns.

Here's a quick summary of suitable converters available:

	Resolution (bits)	Sample Rate (MHz)	Faxcode*
Imaging			
AD775	8	20	1345
AD876/8	8	20	1375/6
AD9058	8	40	1455
AD876	10	20	1838
AD9050	10	40	1843
Color Flow			
AD1672	12	3	1880
AD870	12	10	Call ADI sales
AD872	12	10	1431
AD9022	12	20	1840
AD9026	12	25	1842
AD9042	12	41	1922
Audio			
AD7870A, 75/76	12	100 kHz	1898, 1374/5
AD7871/72	14	83 kSPS	1371/2
AD7874	12 (4-channel)	8 μs/channel	1373
AD7878	12 (8-word FIFO)	100 kHz	1376

Digital signal processors: The number of measurement points, speed, and wide dynamic range of the data that has to be processed requires the use of high-speed digital processors. DSPs perform such tasks as FIR/IIR filtering and computing the AFE time delay variables. The ADSP-21060 (32-bit floating point, 40-MIPS) SHARC DSP processor, with its 4 Mbits of on-chip memory, offers the performance needed in such demanding applications as ultrasound and many other medical imaging applications. If cumulative roundoff errors over many computations don't pose a serious problem for a given system, cost-effective 16-bit fixed-point processors like the ADSP-2171 and ADSP-2181 with on-chip memory and high speed operation offer versatile I/O and up to 33-MIPS performance.

		Faxcode
ADSP-21060	32 bits, 40 MIPS, 4-Mbit internal RAM	1870
ADSP-2171	16 bits, 33 MIPS, on-chip Memory, PROM	1869 (52 pgs)
ADSP-2181	16 bits, enhanced 2171	1927

The processed data is sent to the video display and audio encoder. Triple 8- to 10-bit RAM-DACs, i.e., the ADV family of products, are used to convert digital words to analog for color display. The AD720/721/722 family of analog RGB to NTSC/PAL encoders, combined with video amplifiers like the AD813, AD817/818 and AD826/828 (low cost, good video performance industry standard amplifiers) are used to accommodate the various video standards for display and recording.

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