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Review of Current Simple Ultrasound Hardware Considerations, Designs, and Processing Opportunities

REVIEW

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ABSTRACT

Ultrasound is one of the most widely used imaging tools for non-destructive testing (NDT) and non-invasive medical diagnosis. Since its beginnings in the 1950s, ultrasound imaging research has led to innovations such as new sensors, signal processing, and hardware development. After more than fifty years, the field continues to evolve, aided by advances in electronics and digital hardware. However, the field remains under-researched in terms of experimental open-source hardware. An open, flexible, and cost-efficient platform is still needed for many basic medical and testing applications. A platform of this kind would support the efforts of researchers, makers, and device developers in accelerating ultrasound research and development.

The aim of this review is to identify literature relevant to the understanding, design, and operation of simple ultrasound devices and to present this body of knowledge in a format that is easily accessible to ultrasound system designers. It also provides a summary of current ultrasound research to introduce readers to trends of interest.

We capture design and use considerations from classical and modern instruments. We cover both NDT and medical applications, starting with a review of the design context, followed by a review of existing architectures and analog buildings blocks, followed by a survey of digital options available to support and complement the hardware.

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1 A RENEWED INTEREST IN ULTRASOUND HARDWARE

Ultrasound has been a developing field in medical imaging and non-destructive testing and exploration (NDT/NDE) since the 1950s. Although ultrasound is today a relatively mature technology (Kjeken et al. 2011), it remains an active area of study (Lanza 2020). New technologies, such as capacitive micromachined ultrasound transducers (CMUTs) and compressed sensing (CS) (Kruizinga et al. 2017; Liebgott et al. 2012), have the potential to revolutionize ultrasound imaging and dramatically improve its affordability. Ultrasound imaging has numerous advantages over other widely used imaging modalities, such as computer tomography (CT), X-ray imaging, and magnetic resonance tomography (MRI), particularly because it is deemed safe and affordable (Kurjak and Breyer 1986) and has become an important tool in medical care (S. Wang, Hossack, and Klibanov 2020).

Renewed interest in ultrasound technologies also follows the development of multi-modal devices, i.e., systems that combine ultrasound with electrical, MRI, optical, and tomography imaging modalities. This is especially relevant in light of the recent development of device prototypes capable of producing ultrasound images using only piezoelectric organic light-emitting diodes (H. Yu et al. 2020) and non-contact laser ultrasound systems (X. Zhang et al. 2019). Developments like these have the potential to dramatically change the ultrasound hardware paradigm. Ultrasound technology is also leveraging progress in low-cost computing in order to offload functions which previously required complex and expensive hardware. Ultrasound technology is therefore attracting the attention of researchers, from college students to post-docs (Xu Zhao, Hebden, and Yerworth 2021), who are exploring applications that rely on non-destructive testing or medical imaging.

An open, affordable, and extensible platform for ultrasound research would therefore be a timely development.

Open hardware has been shown to lower barriers to product research (Pandey and Vora 2019) and promote technology use. It can also have a disruptive effect on the ultrasound market by enabling shorter development cycles, allowing for more rapid iterations of products (Joshua M Pearce 2015; J. M. Pearce 2016; Moritz et al. 2019; Winter et al. 2019). It can also enable users to access and repair devices by making use of freely available online documentation and support from the open-source community (Gibney 2016).

2 THE MAIN ULTRASOUND IMAGING MODES

Ultrasound imaging is based on the “pulse-echo” principle, which relies on a piezoelectric transducer functioning in a dual role–as both a transmitter and receiver. Applications of ultrasound technologies cover a wide spectrum of use cases, detailed in ***Table 1***.

The two modes most commonly found in ultrasound equipment are the A- and B-Modes. Doppler imaging and Doppler-related modes, including C-Mode, and spectrogram are exceptions that lie beyond the scope of this review, which focuses on simpler imaging methods.

A-Mode, or amplitude mode, displays the direct amplitude of echoes received as a function of time and creates one-dimensional images. We deem M-Mode an extension of the A-mode, as an A-Mode time motion representation. A-Mode is the building block of B-mode imaging.

B-Mode: B-Mode, in which a 2D image is produced, is the most common form of ultrasound imaging. It displays the envelope of the recorded signal, typically in grey-value representation on a 2D map, where every value is assigned a different shade of grey. The higher the intensity of the echo, the brighter the reconstructed image. This produces the widely known sonogram used to examine babies in utero. Kurjak and Breyer (1986) laid out the basic specifications for a general purpose ultrasound scanner. This minimal specification set, which is captured in early portable devices such as the Sonovisor (Zeiss 1962) or later portable devices (Ligtvoet et al. 1978), allows designers to frame the development of their own systems designed to

- produce B-mode images, which translates as a device having linear- and convex- type scan-heads
- image with a frequency of 3.5 to 5 MHz, for a depth of up to 18 cm

APPLICATION	DESCRIPTION	REFERENCES
NDT/NDE	Ultrasound is commonly used for quality or integrity control of mechanical elements, based on pulse-echo measurement.	L. Zhang 2012; Triger et al. 2008; A. A. Assef, Maia, and Costa 2016; Schueler, H. Lee, and Wade 1984; D. Zhang et al. 2018; Dayi Zhang, R. Watson, MacLeod, et al. 2021; Clementi, Littmann, and Capineri 2020
General imaging	Although it is relatively simple and does not enable 2D imaging, A-mode enables measurements for examinations such as para-nasal sinuses, trans-skull fluid detection, sinus pathology orophthalmology assessments, and even fluid physical properties.	Carotenuto, Caliano, and Caronti 2004; Y. Yang et al. 2021
Non-doppler vascular assessments	Devices were used to measure the diameter and the blood pulse speed traveling through the radial artery, which then can be used to track changes in blood pressure at various points on the human body, or even artery stiffness.	Worthing 2016; Hu, Xingqun Zhao, and L. Xia 2011; D.-l. Zhang et al. 2017; Shomaji et al. 2019; Jayaraj Joseph et al. 2015; J. Joseph et al. 2015; J. Seo 2018
Bone Porosity	Ultrasound measurements have been shown to be a solution to measure evolution of bone indicators, such as porosity.	Wahab et al. 2016; Fontes-Pereira et al. 2018; Gräsel, Glüer, and Barkmann 2017
Body monitoring	Tissue monitoring uses include tissue assessment, for example quantifying neuro-muscular disease progression.	Keyes 2017; X. Zhang 2015; Brausch, H. Hewener, and Lukowicz 2019; D.W. Park, D. C. Park, and Chung 2019; Lowry, Wagner, and Bigler 2021; Zhou, H. Wang, and X. Li 2021
Bladder measurements	Measurement of bladder volumes is also a standard medical care use, though not necessarily for diagnostic purposes.	Kuru et al. 2019
Biofeedback	Ultrasound imaging enables the observation of muscle movements to support the follow-up of biofeedback, for example in stroke reeducation or human-machine interfaces.	Sosnowska, Vuckovic, and Gollee 2019; Sikdar et al. 2014; Kwong et al. 2020; X. Yang, J. Yan, et al. 2020; Y. Li et al. 2016; Boyd, Fang, and H. Liu 2019; Eshky et al. 2021; S. Liu, Zhai, and Han 2021; Xingchen Yang et al. 2018; Jipeng Yan et al. 2019
Movement tracking	Ultrasound has been used in tracking body movements for example, tracking obstructive sleep apnea, breathing patterns, and heart muscle behavior.	Nguyen et al. 2019; Shahshahani et al. 2018; Weng, J.-W. Chen, and C.-C. Huang 2015; Weng, J.-W. Chen, P.-Y. Lee, et al. 2017; Fernandes, Ono, and Ukwatta 2021
Neuromodulation	Ultrasound is used in neuromodulation experiments, including communication with implantable stimulators.	Pashaei, Dehghanzadeh, et al. 2020; Johnson et al. 2018; D. Seo et al. 2016; Santagati, Dave, and Melodia 2020.
Capsule imaging	Typically small devices, which enable endoscopy imaging using high frequency ultrasound by fitting the hardware into relatively small capsules. They promise further development, and their architecture can be a source of inspiration.	Cox et al. 2017; X. Wang et al. 2017; J. H. Lee et al. 2014; Memon et al. 2016; H. S. Lay et al. 2016; H. Lay et al. 2018
Wearables	Aligned with streamlining and increase of affordability of ultrasound miniaturisation, ultrasound fits with wearable requirements and can provide power and communication means for implants.	Basak, Ranganathan, and Bhunia 2013; Kou et al. 2020; X. Yang, Z. Chen, et al. 2019

Table 1 Applications, by group of uses.

- image human tissues with a signal-to-noise ratio (SNR) of at least 50 dB (Attarzadeh, Y. Xu, and Ytterdal 2017), which requires an ADC of at least 9-bits
- display a reconstructed 512 × 512 image, with a depth of 4 bits
- scan a viewing angle of 40 degrees or more, which indicates that 128 lines per image should be sufficient
- refresh the image at 5 to 10- frames per second.

A less commonly used mode, which is beyond the scope of this review, is ***Ultrasound Computed Tomography (USCT)*** (X. Zhang 2015; Duric et al. 2007; Wen et al. 2019; Ashfaq and Ermert

2004; Marwa et al. 2019; Gemmeke et al. 2010). A single transducer or array of transducers is used to measure acoustic impedance at different angles and an image is reconstructed using back-projection or related finite element techniques. In recent research on plane wave acoustic imaging, acoustic impedance methods normally used in tomography have been harnessed to recreate images with high temporal and spatial resolution (Rabut et al. 2019; Warner et al. 2013). New computing techniques for full wave imaging have also opened the door to better imaging (Guasch et al. 2020; Rymarczyk et al. 2019).

3 CONSIDERATIONS LEADING TO THE DESIGN OF THE SYSTEM ARCHITECTURE

3.1 INFORMATION FEEDING INTO THIS REVIEW

Apart from projects aimed specifically at developing open-source ultrasound hardware (Roman 2019; Jonveaux 2017; Jonveaux 2019b), several sources can be consulted to inform the design of new devices.

The main source of information is the scientific literature, which offers insights in terms of research device design and major technology evolution over the years, reflecting both medical and NDT state of the art. A secondary source of information is patents, which are publicly available on the Internet. Teardowns of medical devices available online also provide information about state-of-the-art hardware architecture. However, investigations of this kind are relatively infrequent, as performing teardowns requires that researchers have both specific skills and an interest in dismantling expensive equipment. Refurbished equipment from the ‘80s and ‘90s, such as mechanical probes (Schuette, Norris, and Doppman 1976; Eggleton and Johnston 1975; Skolnick and Matzuk 1978), can be an affordable source of sensors, in addition to providing useful ideas and concepts from a design perspective.

Chip makers are also important sources of knowledge and know-how (Brunner and Com 2002; Xiaochen Xu, Venkatara man, et al. 2010; Xiaochen Xu, Wala, Vishwa, Shen, Dijeesh, et al. 2020), as they are major producers of concept and design notes. Chip makers also provide guidance on system design (Chu n.d.; Xiaochen Xu, Wala, Vishwa, Shen, K, et al. 2021), but integrating components can be challenging. For example, datasheets may be incomplete or erroneous. To support the use of their circuits, chip makers provide evaluation kits, but these may be overly complex and expensive for some users, such as hobbyists.

Finally, we considered features provided by suppliers of research equipment, including Verasonics, Olympus, Optel and Lecoeur Electronique, as detailed in the Supplementary information section.

3.2 FUNCTIONAL BLOCKS OF ULTRASOUND SYSTEMS

The required functions in an ultrasound pulse-echo system (shown in ***Figure 1***) are relatively standard and are well described in the literature (Ali 2008). They consist in a “pulser” creating the high-voltage pulse, a “receiver” protecting the downstream components, a “Time Gain Compensation” (TGC) amplifier to prepare the signal to the “Analog to Digital Converter” (ADC), which digitizes this signal. Several groups of researchers have used this functional approach to design and implement relatively complex, research-friendly equipment (Boni, Bassi, Dallai, Guidi, Meacci, et al. 2016; Boni, Bassi, Dallai, Guidi, Ramalli, et al. 2012; Boni, A. C. H. Yu, et al. 2018; W. Qiu et al. 2012; Lévesque 2011) and simpler designs (Carotenuto, Caliano, Caronti, et al. 2005; Richard, Zar, and Solek 2008; Taylor, Jonveaux, and Caskey 2017). Jonveaux (2017) proposed a module-like Arduino approach to functional blocks, balanced by SNR and cost impacts, and other researchers have adopted a similar approach, proposed by Gołąbek, Rymarczyk, and Adamkiewicz (2019), in their designs.

The functional blocks include a pulser (to create the initial energy transmission), a receiver (to sort between the initial pulse and smaller subsequent signals), a time-gain compensation function (to compensate for depth-related attenuation), and an ADC (to digitize the signals). A controller coordinates these different components in parallel; typically a field-programmable gate array (FPGA) is used rather than a microcontroller. Once digitized, the signal is exported to the user.

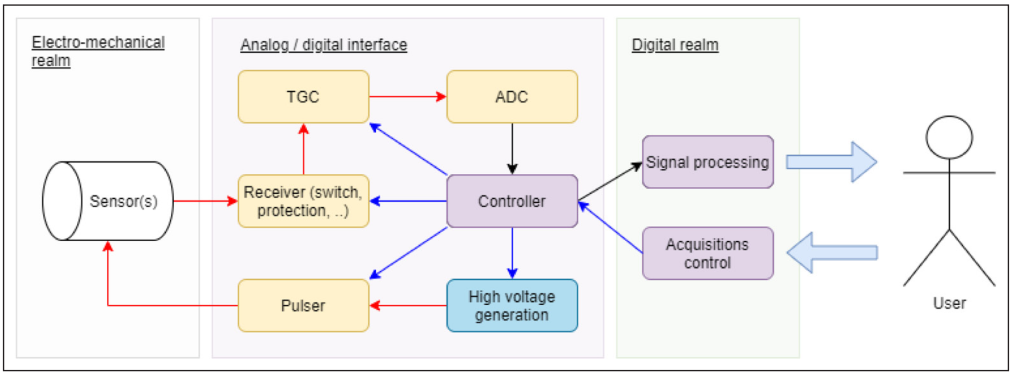

Figure 1 Block diagram of a general ultrasound system. Analog components are in yellow, digital in purple, and high voltage in blue.

These blocks are used to create the pulse-echo pattern that ultimately creates an ultrasound image in either A- or B-mode.

Because the sensors are mostly analog, and due to the low signals they yield, special care must be taken with the analog parts (shown in orange in *Figure 1*) so that a satisfactory analog signal is extracted before digitization. As we will see, these elements can be integrated into single-chip devices.

3.3 STATE OF THE ART AND REVIEW OF THE ULTRASOUND HARDWARE DESIGNS

3.3.1 Design sources for the state of the art review

The objective of this review is to provide an overview of the current state of art and a benchmark for future design specifications for simple ultrasound devices. However, high-end systems were also considered, as it is possible to exploit aspects of their design approach for use on simpler platforms. The design of specific hardware is outside the scope of the current work.

A summary of the literature on ultrasound system design, based on a review of components used, is presented in *Table 2*. Most of these systems were designed for academic research and did not reach the market.

Cost has not been included as production volumes are not specified in the designs, meaning that comparative costs would not yield relevant information.

3.3.2 High-voltage pulser (transmit stage)

There are several options for designing a high-voltage pulser, depending on the required specifications, such as size, power use, voltage range, and cost. A summary of components is presented in *Table 3*.

In contrast to the HV7361 high voltage pulser, the 8-channel HV7351 also allows for predetermined transmit patterns.

3.3.3 Switches

Switches allow the user to select the element of interest, and in some cases, to eliminate use of unwanted high-voltage components. Transmit/receive (T/R) switches are typically used, such as the LM96530 (Vasudevan, P. Govindan, and J. Saniie 2014), MAX14866 (Jonveaux 2021a) or the HV2605, HV2201, HV20220 (H. Li et al. 2014) chips. Switches can be integrated at the pulser level (Worthing 2016; Hidayat et al. 2020) or on the receiving path, for instance, using a LM96530 (Gwirc et al. 2019; Roman et al. 2018).

More simply, clipping devices (the MD0100 used by H. Li et al. (2014), Sharma (2015), or the MMBD4148/MMBD3004) allow clipping of the signal on the receive path to protect downstream processing.

3.3.4 Time Gain Compensation (TGC) Amplifiers

The choice of discrete elements that can be used as amplifiers is relatively limited, and these are typically from the AD8331 family (Gräsel, Glüer, and Barkmann 2017; H. S. Lay et al. 2016; Brunner and Com 2002) or other types of low-noise amplifiers. In order to dynamically adjust

REFERENCE	ELEMENTS	VOLTAGE	MSPS	RES	AFE-TGC	YEAR
Ahn et al. 2015	16	70 V	40	10	AFE5808	2015
A. A. Assef and Maia 2014	128	100 Vpp	50	12	AFE5805	2014
Amauri A. Assef et al. 2012	128	100 Vpp	50	12	AFE5805	2012
Amauri Amorin Assef 2015	NA	100 Vpp	40	12	AFE5805	2015
Batbayar et al. 2018	4 × 32	NA	80	10	NA	2018
Bharath et al. 2018	8	105 V	50	16	AFE5809	2018
R. Bharath, Reddy, et al. 2016	8	+–50 V	40	12	AFE5808	2016
R. Bharath, Chandrashekar, et al. 2015	NA	NA	NA		NA	2015
Chang-hong Hu, Qifa Zhou, and K.K. Shung 2008	1	15 V	120	12		2008
Chatar and M. L. George 2016	16	NA	150	14	NA	2016
Cheung et al. 2012	128	NA	80	10	AD9272	2012
Dusa et al. 2014	8	100 Vpp	65	12	AFE5809	2014
Fournelle et al. 2020	32	+–100 V	40		NA	2020
FRITSCH n.d.	1	50–400 V	80		NA	NA
Pramod Govindan et al. 2015	8	NA	250	8	VCA8500	2015
Pascal Alexander Hager et al. 2017	64	100 Vpp	32,5	12	AFE5851	2017
H. J. Hewener et al. 2012	128	+–75 V	80		AD9273	2012
Ibrahim, S. Zhang, et al. 2018	64	12 V	20	12	NA	2018
Jonveaux 2017	Single	100 Vpp	22	9	AD8331	2018
J. H. Kim et al. 2017	128 (32 ch)	+–80 V	50	12	NA	2017
Kruizinga et al. 2017	Single	100 Vpp	200	12	NA	2017
Kushi and Suresh Babu 2017	Single	NA	100	14	NA	2017
Y. Lee et al. 2014	16	NA	40		AFE5808	2014
H. Li et al. 2014	Single	80 V	40	12	AD9276	2014
Matera et al. 2018	8	6 V	75	14	AFE5809	2018
Nguyen et al. 2019	2	18 V	40	10		2019
Pashaei, Dehghanzadeh, et al. 2020	8	10 V	80	12	AD9276	2020
Peyton, M. G. Boutelle, and Drakakis 2018	32	NA	20		Custom	2018
Weibao Qiu, J. Xia, et al. 2018	Single	+48 V	160		AD8331	2018
Y. Qiu et al. 2020	1	60 V	250	12	TC6320	2020
Ricci et al. 2006	1	100 V	64	14	MAX4107	2006
Roman et al. 2018	64	+–50 V	80	12	AD9276	2018
Vasudevan, P. Govindan, and J. Saniie 2014	Single	100 Vpp	250	12	VCA8500	2014
Wall 2010	NA	12 V	65		NA	2010
Weng, J.-W. Chen, and C.-C. Huang 2015	16	100 V	150	10	Max2077	2015
Q. Zhang et al. 2019	64	100 V	80	14		2019
D.-l. Zhang et al. 2017	8	70 V	250	16	QT1138	2017

Table 2 Review of ultrasound hardware designs, detailing speed of acquisitions (Msps), Resolution (Res.) and features where applicable.

the gain, it is expected that the variable gain amplifier can be finely controlled as a function of time. A typical gain range is between 0 dB and 40 dB to 80 dB (Sharma 2015; Lévesque 2011). The AD8335 is a simpler amplifier with 80 dB gain (Tortoli et al. 2009), while the AD604 (X. Yang, Z. Chen, et al. 2019) is a dual variable amplifier with a gain of 48 dB, which may also be appropriate for simple ultrasound devices.

TYPOLOGY	COMPONENTS	EXAMPLES
Drivers and high voltage FETs	MD1213+MD1711, TC7320+MD1810, EL7158+TC6320	Sharma 2015; Wu et al. 2013; Chu n.d.
Integrated Chips	HV7361/HV7351, HV748, STHV800, STHV748, LM96551 (Note: the 8-channel HV7351 allows for predetermined transmit patterns while the HV7361 does not)	Martins 2017; D.-l. Zhang et al. 2017; H. J. Hewener et al. 2012; Worthing 2016; J. Joseph et al. 2015
Multiplexers/switches	MAX14808	Rodríguez-Olivares et al. 2018; Y. Lee et al. 2014; Garcia 2014; Boni, Bassi, Dallai, Guidi, Meacci, et al. 2016
Signal generator and power amplifier	THS5651A+LT1210CS, TCA0372	Matera et al. 2018; Choi et al. 2020

Table 3 Typology of pulsers described in the literature, grouped by technical approach.

3.3.5 Analog-to-digital converters (ADCs)

Once the signals are amplified, it is relatively easy to match and make full use of the ADC digitization range. In simple designs, single-frequency sensors capable of detecting frequencies from 1 MHz to 15 MHz are often used, leading to designs with ADCs ranging from 40 to 150 Msps, and from 10 to 14 bits. Multi-frequency (X. L. Sun et al. 2018) devices have also been developed (Lukacs, Sayer, and S. Foster 1998; F. S. Foster et al. 2009), and in some cases, "First In/First Out" (FIFO) buffers are used between the ADC and the controller (D. Yang et al. 2009), for example with the AL422B.

3.3.6 Electronic Analog Front-End (AFE)

In more recent designs, ADCs and some or all of the analog components (in yellow in ***Figure 1***) are often integrated in analog front-end chips. This allows for a simpler integrated design, albeit at the expense of making a design more costly and less open. These components integrate the pulser, channel management, amplifier and digitization functions in a single chip. Different families identified in this review include the following:

- *AD927X* systems are widely used and usually have 8 channels, with a 12-bit ADC from 10 MHz to 80 MHz and with time compensation amplifiers (Di Ianni et al. 2016; H. J. Hewener et al. 2012; J. J. R. Raj, S. Rahman, and Anand 2018; Cheung et al. 2012; Alqasemi et al. 2012; Batbayar et al. 2018; Techavipoo et al. 2012).
- The *AFE58XX* family has 8- to 32-channel AFEs from 50–65 MSPS, with LNA, VCAT, PGA, LPF, ADC, and possibly continuous wave (CW) mixer (Amauri Amorin Assef 2015; Amauri A. Assef et al. 2012; A. A. Assef and Maia 2014; A. A. Assef, Maia, and Costa 2016; R. Bharath, Kumar, et al. 2015; R. Bharath, Reddy, et al. 2016; Y. Lee et al. 2014; P. A. Hager, Risser, et al. 2017; Bharath et al. 2018; Kidav et al. 2019).
- Finally, the *MAX2082 and MAX2077* have 8 channels, including a high-voltage pulser and transmit/receive (TR) switch, but offer no digitization capability (H. Hewener et al. 2019; Weng, J.-W. Chen, and C.-C. Huang 2015; J. Seo 2018; Sabbella 2021).

These AFEs all include several channels, which is not necessary for a single-element design, but in multi-channel designs, they can improve space and cost efficiency.

3.3.7 A challenge: high-voltage generation

High-voltage design for ultrasound was a particular point of interest in this review; therefore, we also surveyed the available high-voltage components and sources. Unfortunately, this topic has not received significant consideration in most publications, apart from Xiao et al. (2013). The ideal requirements for a good high-voltage design would be a small footprint, low power consumption, and settable levels between 0 to 90 V, ideally with another source providing 0 to –90 V for bipolar pulses which would usually function with a current supply of 25–30 mA. Brown and Lockwood (2002) achieved 350 V pulses in early designs built with 50 worth of components. However, finding a working design within the ideal parameters is still a challenge today, even with the existing detailed datasheets provided by manufacturers and the schemes published by a few researchers who have shared their designs (Tang and Clement 2014; Granata, Vishwa, and Shen 2020). In the open-source literature, some designs used an expensive RECOM device, providing a 0–120 V range, or an NMT0572SC, providing 24, 48 and 72 V rails, as well as the LT3494 with a rail up to 39 V. Other alternatives were considered, namely the *MAX668* (which operates from O to 150 V), *MAX1856* (between –80 V and –24 V), an *MIC3172* design, using an *HV9150* to reach up to 200 V, or a *MAX15031* of up to 80 V. The *DRV8662* family, including the DRV2700, also has been used to provide rails for up to 105 V. Older devices were observed that made use of integrated devices, such as the PICO 5SM250S DC-DC converter. Larger devices, such as the LM96550, are not suitable due to the importance of physical size.

In order to optimize high-voltage designs for low power consumption, electrical impedance matching (Rathod 2019) must be used to improve the level of energy transmitted to the transducer. Low-cost vector network analyzers (VNAs), like the $ 40 NanoVNA (usable in MHz-range transducers), have allowed for some interesting developments (Garcia-Rodriguez et al. 2010; Wei, H. Chen, and Y. Chen 2020) and can be used to improve the overall signal-to-noise ratio.

3.3.8 Mechanical sweeping

When designing any 2D ultrasound device, the system must be capable of sweeping the target imaging scene. To minimize hardware costs, the space can be imaged by mechanically sweeping a single piezoelectric element across the target scene (Shaw 1977; Matzuk and Skolnick 1978; Wilkinson 1981), which would require only a single channel of electronic hardware for data acquisition (Saijo 2018). This sweeping principle has been used in several experimental setups, including J. H. Chang et al. (2009), and is also used in older mechanical probes, which are based on either continuous rotation of the transducer (e.g., Kretztechnik AR3 4/5B/A, ATL 724A) to accommodate plane sweeping (Holm et al. 1975), sometimes with multiple transducers to allow for multiple images per rotation or with mechanical sweeps (e.g., Interspec Apogee, Diasonics probes, Kretztechnik AW14/5B/A, HP 21412A) (Jonveaux 2019a). This approach was initially more commonly seen in intra-cavity probes, due to space constraints (Hisanaga et al. 1980).

For some applications, such as cardiac scans of small animals, the heartbeat and target size require in excess of 100 frames per second (fps) with a spatial resolution of 100 μm or less. To meet these requirements, Lei (2018) implemented a 30–50 MHz real-time single-element ultrasound device that scans at 130 fps. Higher frequency imaging transducers are relatively smaller in size, which makes them ideal candidates for mechanical sweeping when arrays are too large. However, this implies strong positioning control and precision motors, requiring, for example, optical encoders and piezoelectric motors (Carotenuto, Caliano, and Caronti 2004), with the additional requirement of injecting as little noise as possible into the analog processing path. Other uses of piezoelectric actuators include the use of bimorphs (Bezanson, Adamson, and Brown 2011), which can reach 130fps for electromagnetic motors. Still, the weight borne by the actuator must be limited (Brown, Leadbetter, et al. 2013; C.-H. Huang and Zou 2015), a constraint which can be satisfied using MEMs (Choi et al. 2020) or mobile acoustic mirrors with fixed transducers (Havlice and Taenzer 1979).

In laboratory designs where real-time imaging is not required, XYZ positioning systems with 3D-printed components have been used (Svilainis et al. 2014; B. Wang and Jafar Saniie 2019; K. Xu et al. 2019). For example, N. Bottenus et al. (2016) demonstrated that a three-axis translation stage allowed for precise position and orientation control of the transducer. 1-D systems, e.g., systems built using a transducer on a linear motor stage, can also be used (Weibao Qiu, Y. Yu, Tsang, et al. 2011; Pramod Govindan et al. 2015; Soto-Cajiga et al. 2012; P. Govindan, S. Gilliland, Kasaeifard, et al. 2013; Bou-Hamdan 2021), which allows the system's transducer to sweep across the target scene. Smith, Graham, and Neasham (2015) also uses a single transducer element in combination with a lower noise voice coil motor as the mechanical actuator, a compromise with significant estimated production cost savings (over 95%), while maintaining a relatively noise-free signal.

Alternative displacements methods can be employed, for example, using accelerometers to determine the position of the transducer (Sobhani et al. 2016) or allowing for precise image reconstruction with an Arduino and Raspberry Pi setup (C. Herickhoff, Lin, and Dahl 2019), which can also be used in ultrasound training simulators (Farsoni, Bonfè, and Astolfi 2017). In the case of skin imaging, another option is to use optical trackers similar to those used in computer mice (W.-T. Zhang et al. 2019; Poulsen, Pedersen, and Szabo 2005; C. D. Herickhoff et al. 2018).

3.3.9 Considerations when choosing acoustic materials

In most mechanical designs, an acoustic window made of a material transparent to acoustic waves is needed to seal the scanner mobile head from the external medium while minimizing signal loss. The first mechanical scanners used water-baths as an intermediate between the transducers and the subject (Schueler, H. Lee, and Wade 1984). Materials regularly used for this include polymethylpentene (TPX), which can also be used on high-frequency ultrasound scanners (Erickson, Kruse, and Ferrara 2001; Brown, Leadbetter, et al. 2013), or perspex (Bow et al. 1979). Alternatively, Y. Qiu et al. (2020) use an acoustic window made from polydimethylsiloxane (PDMS), such as Sylgard 184 silicon, which can be used for reference targets, to minimize reflection and attenuation during transmission (Lorenzo et al. 2009; Melde et al. 2016).

In addition to the acoustic window, reference imaging targets (also known as ultrasound phantoms) are important for device development. More common materials can be used for this application, e.g., polyimide (Xiaochen Xu, L. Sun, et al. 2008; Lei Sun et al. 2008) and sealant silicones that mimic soft tissues (Lorenzo et al. 2009). Polyvinyl alcohol and polyurethane, as well as polyvinylidene fluoride (PVDF), have been considered (Sikdar et al. 2014) for device-patient acoustic coupling. Agar and gelatin materials have been used as temporary phantoms (Vogt and Ermert 2005; Chun et al. 2015) where graphite powder reproduces tissue scattering.

3.3.10 Controllers supported by the development of open source FPGAs

The controller presented in ***Figure 1*** as having a central function in ultrasound devices has traditionally been a microcontroller whose limitations are not always compatible with ultrasound chips due to the speed requirements in systems where several parallel communications are taking place simultaneously. One solution to this is to use direct memory access (DMA) optimized microcontroller designs (Kidav et al. 2019). However, due to the increased accessibility of FPGAs, digital signal processors (DSPs) and systems-on-chip (SoCs) (for radio frequency signal processing) are strategic options. Along with the development of integrated AFE, these components have accelerated the creation and availability of high-end programmable research platforms (Roman et al. 2018). In some designs, an additional micro-controller is set up between the FPGA and a USB bus (Pashaei, Roman, and Mandal 2018; Schneider et al. 2010), which can provide the FPGA with a configuration on the fly and allow access to the computation platform to set up the pulse-echo sequence parameters (J. R. Raj, S. M. K. Rahman, and Anand 2017; J. Raj, Smk, and Anand 2016; Weibao Qiu et al. 2013). This uses in particular the Cypress families, either in USB 2 (Hu, Xingqun Zhao, and L. Xia 2011; Richard, Zar, and Solek 2008) or USB 3 (Lewandowski, Sielewicz, and Walczak 2012; Weibao Qiu, J. Xia, et al. 2018; Y. Qiu et al. 2020; Ahn et al. 2015), but also through Ethernet (e.g., with a CP2200) or WiFi. Commercial USB probes can also use a common architecture (Jonveaux 2021c).

FPGAs increase the potential for developing ultrasound imaging systems with small form factors and creating high-performance devices with reduced power consumption (Dusa et al. 2014). Configurable hardware makes the system resilient to future changes: designs can be adjusted without reprinting the circuit board (L. Zhang 2012; Weibao Qiu, Y. Yu, and L. Sun 2010; Ibrahim, Simon, et al. 2017). From an open-source perspective, FPGA use has been supported by the development of new open-source toolchains (Shah et al. 2019), thus opening a key technology to a wider public (Saiz-Vela et al. 2020; Jonveaux 2021b).

FPGAs also allow more flexible connection between systems (Spenser Gilliland, Pramod Govindan, and Jafar Saniie 2016; P. Govindan, S. Gilliland, Gonnot, et al. 2013). Many high-end designs are based on peripheral component interconnect express (PCIe) due to high bandwidth requirements (Zimmermann 2018a; Lewandowski, Sielewicz, and Walczak 2012; Kidav et al. 2019), but the complexity of PCIe is an obstacle to low-cost designs. In Jonveaux (2019b), the Raspberry Pi's 40-pin header was used as a simple, standardized interface for developing extension boards.

3.3.11 Transmission of the digital information – bandwidth reduction

Most microcontrollers lack sufficient bandwidth to digitize and process the full ultrasound signal at radio frequencies. Therefore, microcontroller-based systems typically use a pre-processing channel, possibly including an envelope detector in hardware prior to digitization of the signal so that the signal bandwidth is reduced to that of the amplitude-modulating information. However, envelope detectors in hardware typically have a fixed cutoff frequency, which prevents them from being adaptable to different transducer frequencies.

Another possible technique is the use of quadrature sampling to preserve both amplitude and phase information, combined with frequency downconversion to reduce the bandwidth requirement for data transmission, storage, and processing to that of the ultrasound modulation bandwidth, which can be significantly narrower than the maximum frequency of the signal (Peyton, M. G. Boutelle, and Drakakis 2018). Because frequency downconversion and quadrature sampling are used in software defined radios (SDRs) to capture the modulated information on a radio frequency (RF) carrier (Pascal Alexander Hager 2019; P. A. Hager and Benini 2019), SDR hardware can serve as a drop-in replacement for quadrature sampling hardware, as in the “rtl-ultrasound” open-source project (Meng 2019). As such, demodulation techniques enable shifting signals from higher to lower frequencies, thus allowing for use of slower acquisition techniques and leaner hardware.

4 SIGNAL PROCESSING STEPS

4.1 CONVENTIONAL SIGNAL PROCESSING CONSIDERATIONS

In parallel to the analog hardware modules, the digital component of acquisition systems can provide a flexible platform of choice to implement digital processing techniques. We now present resources describing basic components of the signal processing path, i.e., signal filtering, envelope detection, signal compression and scan conversion (Basoglu et al. 1998).

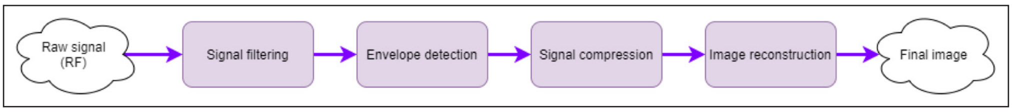

Figure 2 Block diagram of the signal processing path.

Signal processing has one goal: to extract the right information from the raw electrical signal and present it to the user as actionable information (***Figure 2***).

Upstream, ***general filtering*** has commonly been incorporated early in the processing pipeline, often close to the ADC via DSPs and FPGAs, to remove unwanted noise from RF signals while preserving the bandwidth of interest (Amauri Amorin Assef, J. d. Oliveira, et al. 2019; Levesque and Sawan 2009). This ensures a clean signal for further processing.

Once the signal is cleaned, it is possible to extract the information from the radio-frequency signal, which is provided by the ***envelope detection*** step. It transforms the RF signal into a human-readable image, for example using a Hilbert transform. Different envelope-detection methods and algorithms have been explored in DSPs and FPGAs (J. Chang, J. Yen, and K. Shung 2007; Amauri Amorin Assef, J. d. Oliveira, et al. 2019; Amauri Amorin Assef, Ferreira, et al. 2018).

At this stage, and for B-Mode imaging, ***deconvolution*** can be used to remove the usual blur of a single point image, which occurs due to the transducer geometry. The size of the blur in relation to the actual dimension of the point source is a measure of the resolution of the system. To record this behaviour, a point-spread function (PSF) is measured, i.e., the “impulse response” of the system. Knowing a system’s PSF makes improving the image resolution an inverse problem (Jørgen Arendt Jensen et al. 1993; Dalitz, Pohle-Frohlich, and Michalk 2015) and establishes the possibility of recursively reconstructing the true position and shape of the point through deconvolution (Dalitz, Pohle-Frohlich, and Michalk 2015).

Once the image is assembled, ***amplitude compression*** can be used to further reduce the transfer rates needed between hardware and software, which can often produce bottlenecks. In this sense, having upstream compression would alleviate these bottlenecks (Soto-Cajiga et al. 2012; Akkala, Rajalakshmi, et al. 2014). Alternatives include adjusting high electronics dynamic ranges (12 bits and more) to the 8 bits of LCDs and CRTs, for example using the ITU-T G.711 standard (or the a-law) used in sound compression (Akkala, R. Bharath, et al. 2014; Boonleelakul et al. 2013).

Image reconstruction is the last step necessary for producing human-readable images. In the case of mechanical sweeping of an imaging area or volume, the scanned data may not correspond to a Cartesian grid, so a coordinate mapping step, known as a scan conversion, is often necessary before displaying the captured image. Several algorithms have been developed to tackle this issue (Ophir and Maklad 1979), with a focus on real-time requirements (Csány, Szalai, and Gyöngy 2019).

4.2 RECENT SIGNAL PROCESSING CONSIDERATIONS

Element sensors are often focused at a fixed depth, but outside of this depth, the resolution quickly degrades. This can can be alleviated by using ***Synthetic Aperture Focusing (SAF)*** (Andresen, S. I. Nikolov, and J. A. Jensen 2011; Amauri Amorin Assef 2015; LI et al. 2018; Lewandowski, Sielewicz, and Walczak 2012; H. K. Zhang, Cheng, et al. 2016). Other synthetic aperture techniques have been widely discussed, for example in Romero-Laorden et al. (2013), Jeon et al. (2019), and Lim, H. H. Kim, and Yoon (2021), and an earlier article by Burckhardt, Grandchamp, and Hoffmann (1974). Similarly, monostatic synthetic aperture scanners (MSASs) and monostatic fixed focus scanners (MFFSs) are two approaches worth consideration in terms of improving image quality (Nick Bottenus et al. 2015; Ylitalo and Ermert 1994; Heuvel et al. 2017; S. Nikolov, J. Jensen, and Tomov 2008).

At the pulser stage, ***barker codes*** (Dayi Zhang, R. Watson, Dobie, et al. 2019; Xiaochun Wang et al. 2021) can be used to improve image resolution by shaping the excitation signal itself (Isla and Cegla 2017). Researchers have shown that it is possible to improve lateral as well as axial resolution in this manner (Fujita and Hasegawa 2017; Chun et al. 2015; Jung Hoon Kim et al. 2018).

Compressed sensing (CS) (Liutkus et al. 2014; Hua, Yuchi, and Ding 2011; Mitrovic et al. 2020; Ghanbarzadeh-Dagheyan et al. 2021) is a more complex approach to the signal shaping and receiving, which allows for reconstruction of a signal with fewer samples than dictated by the Nyquist-Shannon sampling theorem. Starting with time reversal applications (Gabriel Montaldo et al. 2004; G. Montaldo et al. 2005; Sarvazyan, Fillinger, and Gavrilov 2009), compressing measurements before sensing enables new ultrasound applications (Yisak Kim, J. Park, and H. Kim 2020). With these techniques, it is possible to encode individual volume pixels or voxels using a chaotic medium (Luong, Hies, and Ohl 2016), which allows 3D imaging using a single-element ultrasound sensor and opening doors to simpler hardware and new applications (Kruizinga et al. 2017). Thus far, research has focused on creating phase encoding masks (Meulen et al. 2017; Fedjajevs 2016) or even using random interference to improve image resolution (Ni and H.-N. Lee 2020).

Machine learning (ML) has also shown promise for both image quality improvement (R.Wang et al. 2019; H. Hewener et al. 2019) and support for image interpretation (Divya Krishna et al. 2016), even in A-mode (Brausch and H. Hewener 2019). ML can also be applied to texture imaging, as earlier proposed in a review titled “Average Higuchi Dimension of RF Time series” (Moradi et al. 2006), and to non-imaging techniques, such as mixing monitoring (Bowler, Bakalis, and N. J. Watson 2020).

5 CONCLUSION

Researchers have identified ultrasound as a safe, low-cost solution in medically under-served regions and markets with rising healthcare costs. Interest in ultrasound systems is also increasing in private-sector research and development, as evidenced by the abundance of recent works and new projects exploring innovative aspects of this technology.

The number of more complex, functional ultrasound designs appears to have grown, in general due to the increased availability of sophisticated electronic components and AFE integration of additional analog channels. In addition, compressed sensing allows for dramatic improvements in image quality while reducing the number of sensors and the corresponding hardware required. However, these more sophisticated designs require rapid logic control, which is currently challenging to implement from an open-source perspective.

While examples of open-access documents about ultrasound hardware are limited and no open designs are currently available on the market, sufficient information appears to be available from the literature to produce a proof-of-concept open system that offers a safe, cheap and portable alternative to other imaging technologies. The academic literature demonstrates the utility of open-source design, not only from a medical perspective but also for the purposes of research and education. More sophisticated systems will surely emerge from existing open designs, building on recently developed components and new controllers.

Open-source hardware has the potential to change the shape of ultrasound research by providing replicable systems customized to specific applications, addressing both niche needs and accessible lower-end requirements.

In general, open source ultrasound hardware research is accelerating, and it is our hope that this article will encourage other researchers, manufacturers and makers to share their work.

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

Equipment providers include:

- Avtech (Weibao Qiu and Zheng 2020; Lei 2018),
- Biosono (Biosono 2020; R. Bharath, Kumar, et al. 2015),
- Eurosonic (Jin et al. 2017; Mostavi et al. 2017; Ranachowski et al. 2020; Vadalma 2020),
- Lecoeur Electronique (LeCoeur 2020; Tortoli et al. 2009; H. K. Zhang, Younsu Kim, et al. 2018; Al-Aufi et al. 2019),
- MKC (D. W. Park, D. C. Park, and Chung 2019),
- Olympus (Veenstra 2020; Choi et al. 2020; Chun et al. 2015; X. Xu, J. T. Yen, and K. K. Shung 2007),
- Optel (Scholle and Sinapius 2018; Ratajski and Trajer 2017; Nowak and Markowski 2020; Karjalainen et al. 2012),
- Osun (Vadalma 2020; R. Bharath, Kumar, et al. 2015),
- Ultratek (Veenstra 2020; Pérez-Sánchez et al. 2020; C.-K. Chen et al. 2016; Xianghong Wang et al. 2019)
- Verasonics (Peyton, M. Boutelle, and M. Drakakis 2017; S. S. George, M. C. Huang, and Ignjatovic 2018; Kang et al. 2017; Pascal Alexander Hager et al. 2017)
- or the Fraunhofer Institute (Zimmermann 2019; Zimmermann 2018b; Zimmermann 2018a)

Other suppliers have made smaller contributions to the literature (Ozdemir 2018), such as Socomate (Gil-Alba et al. 2019), MATEC TB-1000 (Kiełczyński et al. 2017) JSR Ultrasonics (Cramer, Perey, and Yost 2015), or high-speed Dr Hillger's USPC (HILLGER 2016).

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