Review of current simple ultrasound hardware considerations, designs, and processing opportunities

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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 1970s, ultrasound imaging has been an ongoing field of research, with innovations such as new sensors, signal processing, and hardware development. After more than fifty years, the field still presents active developments, aided by advances in electronics and digital hardware.

However, within the realm of open-source equipment, the field remains under-researched in terms of experimental hardware. An open, flexible and cost-efficient platform is still needed for many medical and testing basic applications to support the efforts of the researchers, makers and device developers, to accelerate ultrasound research and development.

The aim of this review is to identify literature that is relevant for understanding, designing and operating a simple ultrasound device, and to capture this body of knowledge and make it accessible to ultrasound system designers. It also aims at presenting current ultrasound research focus points to introduce the reader to trends of interest.

We try to capture design and use considerations from older and newer designs. We have covered both NDT and medical applications, starting with a review of the context, following on the review of existing architectures and analog buildings blocks, then on digital options available to support and complement the hardware aspects.

This body of knowledge was used for designing two relatively simple open hardware designs.

**Key words:** ultrasound hardware open-source frugal device imaging modular design

1 A renewed interest in ultrasound hardware

Ultrasound has been a developing field for 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 field of study. 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 drastically improve its affordability. Ultrasound imaging has numerous advantages over other widely-used imaging modalities, such as computer tomography (CT), X-ray imaging or 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.

Renewed interest in ultrasound technologies also is the development of multi-modalities devices, systems that combine ultrasound with electrical, MRI, optical and tomography imaging modalities, especially in light of the recent piezoelectric organic light-emitting diodes [Yu et  al., 2020], or non-contact laser ultrasound [Zhang et  al., 2019c]. These developments have the potential to drastically change the ultrasound hardware paradigm.

It would therefore make sense to build an open, affordable and extensible platform for ultrasound research that leverages progress in low-cost computing in order to offload functions which previously required dedicated hardware.We keep an open-hardware approach for this review, as open-hardware has been shown to lower barriers to product research [Pandey and Vora, 2019],and can have a disruptive effect on the ultrasound market by enabling shorter development cycles, which allows for more rapid iterations of products [Pearce, 2015, Pearce, 2016, Moritz et  al., 2019, Winter et  al., 2019] as well as allowing users to access and repair devices, Using freely-available online documentation and support from the open source community [Gibney, 2016].

2 The main ultrasound imaging modes

With the exception of Doppler imaging, ultrasound imaging is based on the "pulse-echo" principle, which relies on the dual receiver-transmitter function of a piezoelectric transducer. For the sake of the present review, we would voluntarily discard the review of M-Mode, C-Mode, and Doppler modes, which lie beyond the scope of simple imaging methods. The two main modes commonly found in ultrasound equipment are:

***A-Mode***, or amplitude mode, is used to display the direct amplitude of echoes received as a function of time and creates one-dimensional images. This is the building block of B-mode imaging.

***B-Mode***: in B-Mode ultrasound, the most common form of ultrasound imaging, a 2D image is produced. It displays the envelope of the recorded symbols, 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 reflection interface in the reconstructed image. This is the widely known sonogram used to examine babies in utero. As a reference for the next sections, the reviewed literature offers a view of a minimal B-mode imaging system, in particular thanks to [Kurjak and Breyer, 1986] who laid out the basic specifications for a general purpose ultrasound scanner. This basic, minimal specification set can allow designers to frame the development of their own systems, captured in precursor portable devices such as with the Sonovisor [Zeiss, 1962], which would have to be able to:

• image with a frequency of at least 3.5MHz – extendable to 5MHz

• image human tissues with at least 50dB of SNR [Attarzadeh et  al., 2017], which requires at least a 9-bit ADC

• display a reconstructed 512 x 512 image, with a depth of 4 bits

• images to a depth of 18cm

• 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 10fps.

A less commonly used mode is ***tomography***. Though less common than the previously discussed uses, ultrasound can be used in tomography for imaging soft tissue [Zhang, 2015, Duric et  al., 2007, Wen et  al., 2019, Ashfaq and Ermert, 2004]. 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. The same acoustic impedance methods used in tomography have also been used to recreate images with high temporal and spatial resolution in recent research on plane wave acoustic imaging [Rabut et  al., 2019, Warner et  al., 2013]. Recent acoustoelectric imaging systems are able to combine the acoustic image with a current-source density image, suggesting promising novel applications in electrophysiology [Berthon et  al., 2017, Qin et  al., 2017]. New computing techniques for full wave imaging have also the opened door to better imaging [Guasch et  al., 2020, Rymarczyk et  al., 2019].

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Type | Application | Description | References |  |
| A- and B-Mode | NDT/NDE | Ultrasound is commonly used for quality or integrity control of mechanical elements, based on pulse-echo measurement. | [Zhang, 2012, Triger et  al., 2008, Assef et  al., 2016, Schueler et  al., 1984] |  |
| A-Mode | 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. | [noa, , Carotenuto et  al., 2004] |  |
| A- and B-Mode | 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 et  al., 2011, Zhang et  al., 2017, Shomaji et  al., 2019] [Joseph et  al., 2015a, Joseph et  al., 2015b, Seo, 2018] |  |
| A-Mode | 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 et  al., 2017] |  |
| A- and B-Mode | Body monitoring | Tissue monitoring uses include tissue assessment, for example quantifying neuro-muscular disease progression. | [Keyes, 2017, Zhang, 2015, Brausch et  al., 2019] |  |
| A- and B-Mode | Bladder measurements | Measurement of bladder volumes is also a standard medical care use, though not necessarily for diagnostic purposes. | [Kuru et  al., 2019] |  |
| A- and B-Mode | Biofeedback | Ultrasound imaging enables the tracking of muscle movements support the follow-up of biofeedback, for example in stroke reeducation . | [Sosnowska et  al., 2019, Sikdar et  al., 2014] |  |
| A- and B-Mode | 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 et  al., 2015] |  |
| A- and B-Mode | Neuromodulation | Ultrasound is used in neuromodulation experiments. | [Pashaei et  al., 2020, Johnson et  al., 2018, Seo et  al., 2016, Santagati et  al., 2020]. |  |
| B-Mode | Capsule imaging | Typically small devices, which enable endoscopy imaging using high frequency ultrasound by fitting the hardware into relatively capsules. They promise further development, and their architecture can be a source of inspiration. | [Cox et  al., 2017, Wang et  al., 2017, Lee et  al., 2014a, Memon et  al., 2016, Lay et  al., 2016, Lay et  al., 2018] |  |
| A-Mode | Wearables | Aligned with streamlining and increase of affordability of ultrasound miniaturisation, ultrasound fits with wearable requirements and even can provide powering and communication means for implants. | [Basak et  al., 2013, Kou et  al., 2020]. |  |

Table 1: Different applications of the A-mode and B-mode

3 Considerations leading to the design of the system architecture

The following section provides an overview of the available hardware architectures for ultrasound devices.

3.1 Information feeding in the review

Apart from the projects aimed at developing open-source ultrasound hardware described in this article [Roman, 2019, Jonveaux, 2017, Jonveaux, 2019], several sources can be consulted to inform the design stage.

The main source of information has been a scientific literature review, offering insights in terms of research devices designs and major technology evolution over the years, reflecting both medical and NDT state of the art.

A secondary source of information has been patents, as made publicly available on the Internet.

Teardowns of medical devices available online have also provided information about the state of the art in terms of hardware architecture. However, investigations of this kind are relatively infrequent, as this activity requires that researchers have both specific skills and interest in dismantling expensive equipment. Refurbished equipment from the 80s and 90s, such as mechanical probes, can be an affordable source of sensors, in addition to providing useful ideas and concept from a design perspective.

Chip makers can be considered actors in the diffusion of knowledge and know-how [Brunner and Com, 2002, Xu et  al., 2010], as they are major producers of concept and design notes. Chip makers also provide guidance on designs [Chu, ], but integrating these components can be challenging. For example, datasheets may be incomplete or erroneous. To support the use of their circuits, chip makers have also proposed evaluation kits – but these may be overly complex for a simple hobbyist, in addition to being somewhat expensive.

Finally, equipment suppliers provide researchers with similar equipment, making it possible to better understand the required functionalities. They include:

• Avtech [Qiu and Zheng, 2020, Lei, ],

• Biosono [Biosono, , Bharath et  al., 2015b],

• Eurosonic [Jin et  al., 2017, Mostavi et  al., 2017, Ranachowski et  al., 2020, Vadalma, 2020],

• Lecoeur Electronique [LeCoeur, , Tortoli et  al., 2009, Zhang et  al., 2018, Al-Aufi et  al., 2019],

• MKC [Erreur : source de la référence non trouvée],

• Olympus [Veenstra, , Choi et  al., 2020, Chun et  al., 2015, Xu et  al., 2007],

• Optel [Scholle and Sinapius, 2018, Ratajski and Trajer, 2017, Nowak and Markowski, 2020, Karjalainen et  al., 2012],

• Osun [Vadalma, 2020, Bharath et  al., 2015b],

• Ultratek [Veenstra, , Pérez-Sánchez et  al., 2020, Chen et  al., 2016, Wang et  al., 2019b]

• Verasonics [Peyton et  al., 2017, George et  al., 2018, Kang et  al., 2017, Hager et  al., 2017b]

• 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 [KieŃczyński et  al., 2017] JSR Ultrasonics [Cramer et  al., 2015], or high-speed Dr Hillger’s USPC [HILLGER, 2016].

3.2 Functional blocks composing ultrasound systems

The functions required in an ultrasound pulse-echo system (shown in Figure 1) are relatively standard and are well described in the literature [Ali, 2008]. This functional approach has been the one used by several groups of researchers who have worked on designing and implementing relatively complex research-friendly equipment [Boni et  al., 2016, Boni et  al., 2012, Boni et  al., 2018, Qiu et  al., 2012, Lévesque, 2011], even with simpler designs [Carotenuto et  al., 2005, Richard et  al., 2008, Taylor et  al., 2017]. [Jonveaux, 2017] proposed an Arduino, module-like approach to functional blocks, balanced by SNR and cost impacts, which may have inspired further designs [GoŃabek et  al., 2019].

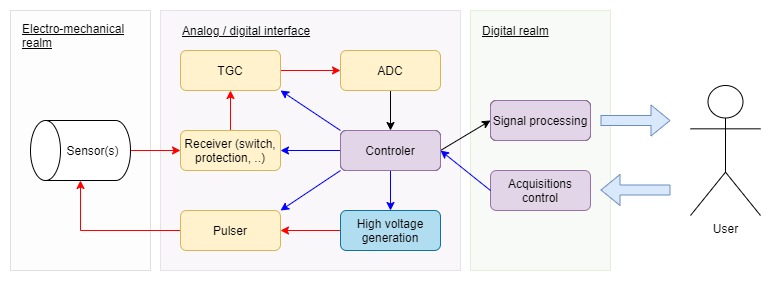


Figure 1: Block diagram of a general ultrasound system. Analog components are in yellow, digital in purple, and high voltage in blue.

These blocks are used to create the pulse-echo pattern that ultimately creates an ultrasound image, be in in A-mode or B-mode. We will see that the analog elements, in yellow, 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

A summary of the literature with respect to ultrasound system design, based on a review of components used, is presented in the table below. High-end systems were considered in this review, as it is possible to exploit aspects of their design approach for use on simpler platforms.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Reference** | **Elements** | **Voltage** | **Msps** | **Res** | **AFE-TGC** | **Year** |
| [Ahn et  al., 2015] | 16 | 70V | 40 | 10 | AFE5808 | 2015 |
| [Assef et  al., 2014] | 128 | 100 Vpp | 50 | 12 | AFE5805 | 2014 |
| [Assef et  al., 2012] | 128 | 100 Vpp | 50 | 12 | AFE5805 | 2012 |
| [Assef et  al., 2015] | NA | 100 Vpp | 40 | 12 | AFE5805 | 2015 |
| [Batbayar et  al., 2018] | 4x32 | NA | 80 | 10 | NA | 2018 |
| [Bharath et  al., 2018] | 8 | 105V | 50 | 16 | AFE5809 | 2018 |
| [Bharath et  al., 2016] | 8 | +-50V | 40 | 12 | AFE5808 | 2016 |
| [Bharath et  al., 2015a] | NA | NA | NA |  | NA | 2015 |
| [Chang-hong Hu et  al., 2008] | 1 | 15V | 120 | 12 |  | 2008 |
| [Chatar and 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 |
| [FRITSCH, ] | 1 | 50-400V | 80 |  | NA | NA |
| [Govindan et  al., 2015] | 8 | NA | 250 | 8 | VCA8500 | 2015 |
| [Hager et  al., 2017b] | 64 | 100Vpp | 32,5 | 12 | AFE5851 | 2017 |
| [Hewener et  al., 2012] | 128 | +-75V | 80 |  | AD9273 | 2012 |
| [Ibrahim et  al., 2018] | 64 | 12 V | 20 | 12 | NA | 2018 |
| [Jonveaux, 2017] | Single | 100Vpp | 22 | 9 | AD8331 | 2018 |
| [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 |
| [Lee et  al., 2014b] | 16 | NA | 40 |  | AFE5808 | 2014 |
| [Li et  al., 2014] | Single | 80 V | 40 | 12 | AD9276 | 2014 |
| [Matera et  al., 2018] | 8 | 6V | 75 | 14 | AFE5809 | 2018 |
| [Nguyen et  al., 2019] | 2 | 18V | 40 | 10 |  | 2019 |
| [Pashaei et  al., 2020] | 8 | 10V | 80 | 12 | AD9276 | 2020 |
| [Peyton et  al., 2018] | 32 | NA | 20 |  | Custom | 2018 |
| [Qiu et  al., 2018] | Single | +48V | 160 |  | AD8331 | 2018 |
| [Qiu et  al., 2020] | 1 | 60V | 250 | 12 | TC6320 | 2020 |
| [Ricci et  al., 2006] | 1 | 100 V | 64 | 14 | MAX4107 | 2006 |
| [Roman et  al., 2018] | 64 | +-50V | 80 | 12 | AD9276 | 2018 |
| [Vasudevan et  al., 2014] | Single | 100 Vpp | 250 | 12 | VCA8500 | 2014 |
| [Wall, 2010] | NA | 12 V | 65 |  | NA | 2010 |
| [Weng et  al., 2015] | 16 | 100V | 150 | 10 | Max2077 | 2015 |
| [Zhang et  al., 2019a] | 64 | 100V | 80 | 14 |  | 2019 |
| [Zhang et  al., 2017] | 8 | 70V | 250 | 16 | QT1138 | 2017 |

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

3.3.2 High voltage pulser (transmit stage)

There are several options to design a high voltage pulser, depending on the required specifications, such as size, power use, voltage range, or cost. A summary pf components is presented below.

|  |  |  |
| --- | --- | --- |
| **Typology** | **Components** | **Examples** |
| Drivers and high voltage FETs | MD1213+MD1711, TC7320+MD1810 , EL7158+TC6320 | [Sharma, 2015, Wu et  al., 2013, Chu, ] |
| Integrated Chips | HV7361/HV7351, HV748, STHV800, LM96551 | [Martins, 2017, Zhang et  al., 2017, Hewener et  al., 2012, Worthing, 2016] |
| Multiplexers/switches | MAX14808 | [Rodrí guez-Olivares et  al., 2018, Lee et  al., 2014b, Garcia, 2014, Boni et  al., 2016] |
| Signal generator and power amplifier | THS5651A+LT1210CS, TCA0372 | [Matera et  al., 2018, Choi et  al., 2020] |

Table 3: Pulsers, by approach

Contrarily to the HV7361, the 8-channel HV7351 also allows for predetermined transmit patterns.

3.3.3 Switches

Switches allow to select the element of interest, as well as possibly remove unwanted high voltage components. Transmit / receive (T/R) switches are used there, such as LM96530 [Erreur : source de la référence non trouvée, Vasudevan et  al., 2014], the MAX14866 or the HV2605, HV2201, HV20220 [Li et  al., 2014] chips. Switches can be integrated at the pulser level [Worthing, 2016, Hidayat et  al., 2020] or on the receiving path, with a LM96530 [Gwirc et  al., 2019, Vasudevan et  al., 2014, Roman et  al., 2018].

More simply, clipping devices (MD0100 [Li et  al., 2014, Sharma, 2015], MMBD4148/MMBD3004 [Chu, ]) allow clipping of the signal on the receive path to protect it.

3.3.4 Amplifiers

Choice of discrete elements as amplifiers is relatively limited, from the AD8331 family [Gräsel et  al., 2017, Lay et  al., 2016, Brunner and Com, 2002], or low noise amplifiers. In order to dynamically adjust the gain, it is expected that the variable gain amplifier can be finely controlled as a function of time. The gain range would usually range between 0dB and 40dB to 80dB [Sharma, 2015, Lévesque, 2011]. The AD8335 is a simpler amplifier with 80dB gain [Tortoli et  al., 2009].

3.3.5 Analog to digital converters (ADCs)

Once the signals amplified, it is relatively easier to match the ADC range and make a full use of its digitization range. As such, most of the designs present ADCs mostly ranging from 10 to 14 bits, and speeds from 40 to 150 Msps, depending on the sensors frequency.

3.3.6 Electronic Analog Front-End (AFE)

In more recent designs, ADCs and some or part of the analog components (in yellow in Fig 1) are often integrated in analog front-end chips, which allow for a simpler integrated design, albeit at the expense of making a design more expensive and less open. These components integrate the pulser, channels management, amplifier and digitization functions in a single chip. Different families were identified during this review.

• *AD927X* systems usually have 8 channels, with a 12-bit ADC from 10 MHz to 80 MHz, with time compensation amplifiers, widely used [Di  Ianni et  al., 2016, Hewener et  al., 2012, Raj et  al., 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 50-65MSPS, with LNA, VCAT, PGA, LPF, ADC, and possibly Continuous Wave (CW) Mixer [Assef et  al., 2015, Assef et  al., 2012, Assef et  al., 2014, Assef et  al., 2016, Bharath et  al., 2015b, Bharath et  al., 2016, Lee et  al., 2014b, Hager et  al., 2017a, Bharath et  al., 2018, Kidav et  al., 2019].

• Finally, the *MAX2082 and MAX2077* have 8 channels, including a high voltage pulser and transmit/receive switch (TR switch), but offer no digitization capability [Hewener et  al., 2019, Weng et  al., 2015].

These AFEs all include several channels, which is not necessary for a single-element design. However, AFEs may still be useful in multi-channel designs in order to improve space and cost efficiency, and may prove useful in posterior design with improving controllers.

3.3.7 A challenge: high-voltage generation

High-voltage components were also reviewed, however, the topic of efficient high-voltage sources is not considered in most publications, apart from [Xiao et  al., 2013The ideal requirements for a good high-voltage design would involve developing a unit with a small footprint, low power consumption, and settable levels between 0 to 90V – ideally with another source for 0 to -90V for bipolar pulses – which would usually function with a current supply of 25-30mA. Early designs [Brown and Lockwood, 2002] achieved 350V pulses with $50 but finding a working design is still a challenge today. In addition, only few researchers are sharing their designs [Tang and Clement, 2014], even considering existing detailed datasheets provided by manufacturers [Granata et  al., 2020

In order to optimize power consumption, electrical impedance matching [Rathod, 2019] has to be used to improve the level of energy transmitted to the transducer, especially with low-cost vector network analyzer (VNAs), like the 40$ NanoVNA, usable in MHz-range transducers), which has allowed for some interesting developments [Garcia-Rodriguez et  al., 2010, Wei et  al., 2020] and can be used for improving the overall signal-to-noise ratio.

3.3.8 Mechanical sweeping

When designing any 2D ultrasound imager, a system capable of sweeping the space to be imaged is required. To minimize hardware costs, the space can be imaged by mechanically sweeping a single piezoelectric element across the target scene, therefore requiring only a single channel of electronic hardware for data acquisition [Saijo, ]. This sweeping principle has been used in several experimental setups, including [Chang et  al., 2009], and was used in older mechanical probes, which are based on either continuous rotation (Kretztechnik AR3 4/5B/A, ATL 724A, ... ) of the transducer to accommodate plane sweeping, sometimes with multiple transducers to allow for multiple images per rotation or with mechanical sweeps (Interspec Apogee, Diasonics probes, Kretztechnik AW14/5B/A, HP 21412A, ... ). This approach was initially more commonly seen in intra-cavity probes, due to space constraints.

For cardiac scans of small animals, heartbeat and target size require in excess of 100 frames per second (fps) with a spatial resolution of 100um or less: [Lei, ] implemented for example a 30-50 MHz real-time ultrasound single-element device that scans at 130 fps. Higher frequencies 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 encoder and piezoelectric motors [Carotenuto et  al., 2004], with a requirement of injecting as little noise as possible on the analog processing path. Other uses of piezoelectric actuators include the use of bimorphs [Bezanson et  al., 2011], reaching 130fps for electromagnetic motors. Still, the weight borne by the actuator has to be limited [Brown et  al., 2013, Huang and Zou, 2015], a constraint also satisfied by MEMs [Choi et  al., 2020].

In laboratory designs where real-time imaging is not required, XYZ positioning systems with 3D-printed components have been used [Svilainis et  al., 2014, Wang and Saniie, 2019, Xu et  al., 2019]. [Bottenus et  al., 2016], for example, demonstrated that a three-axis translation stage allowed for precise position and orientation control of the transducer. 1-D systems, for example based on a transducer on a linear motor stage, can also be used [Qiu et  al., 2011, Govindan et  al., 2015, Soto-Cajiga et  al., 2012], which allows the system’s single transducer to sweep across the target scene. [Smith et  al., 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 keeping a relatively noise-free signal.

Alternative displacements methods can be used, 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 [Herickhoff et  al., 2019], which can also be used in ultrasound training simulators [Farsoni et  al., 2017]. In the case of skin imaging, another example is to use optical trackers like those used in computer mice [Zhang et  al., 2019b, Poulsen et  al., 2005, 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 et  al., 1984]. A material regularly used for this is polymethylpentene, which can be used for example on hand-held high-frequency ultrasound scanners [Erickson et  al., 2001, Brown et  al., 2013]. Alternatively, [Qiu et  al., 2020] uses an acoustic window made from polydimethylsiloxane (PDMS, such as the silicon Sylgard 184) to minimize reflection and attenuation during the ultrasound transmission, which can be used for reference targets [Lorenzo et  al., 2009, Melde et  al., 2016].

More common materials can also be used. For example, polyimide can be used in ultrasound phantoms (reference imaging targets) [Xu et  al., 2008, Lei Sun et  al., 2008], as well as sealant silicones [Lorenzo et  al., 2009] that mimic soft tissues. Polyvinyl alcohol or polyurethane, in addition to polyvinylidene fluoride (PVDF), have been be considered [Sikdar et  al., 2014] for device-patient acoustic coupling. Agar and gelatin are used on temporary phantoms [Vogt and Ermert, 2005, Chun et  al., 2015], where graphite powder reproduces tissue scattering, with no concrete application for the design of devices per se.

3.3.10 Controlers are piggy-backing on the development of open source FPGAs

The controller, seen in Fig 1 as having a central function in ultrasound devices, has traditionally be a microcontroller, which had limitations not always compatible with ultrasound chips coordination as this happens fast, with several parallel communication taking place at the same time. A solution to was to use Direct Memory Access (DMA) optimized microcontroller designs [Kidav et  al., 2019]. However, thanks to the increasing accessibility of field-programmable gate arrays (FPGAs), digital signal processors (DSP), and systems-on-chip (SoC) for radio frequency signals processing is a strategic option. Along with the development of integrated AFE, they 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 et  al., 2018, Schneider et  al., 2010], which can provide the FPGA with a configuration on the fly, and allowing access to the computation platform to set up the pulse-echo sequence parameters [Raj et  al., 2017, Raj et  al., 2016], using in particular the Cypress families, either in USB 2 [Hu et  al., 2011, Richard et  al., 2008] or USB 3 [Lewandowski et  al., 2012, Qiu et  al., 2018, Qiu et  al., 2020, Ahn et  al., 2015].

FPGAs improve 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 [Zhang, 2012, Qiu et  al., 2010, Ibrahim 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].

FPGA allow more flexible connection between systems. Many high-end designs are based on peripheral component interconnect express (PCIe) due to high bandwidth requirements [Zimmermann, 2018a, Lewandowski et  al., 2012, Kidav et  al., 2019], but the complexity of PCIe is an obstacle to low-cost designs. In [Jonveaux, 2019], 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 a 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 et  al., 2018]. Because frequency downconversion and quadrature sampling are used in software defined radios (SDRs) [Hager, 2019, Hager and Benini, 2019] to capture the modulated information on a radio frequency (RF) carrier, 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 would allow shifting signals from higher frequencies to lower, allowing slower acquisition techniques and leaner hardware.

4 Signal processing steps

4.1 Conventional signal processing considerations

In parallel to the hardware analog part, the digital component of acquisition systems is used, through its intrinsic flexibility, to provide a platform of choice to implement digital processing techniques. Now that we have covered the hardware aspects of the research, we now aim to provide the reader with resources describing an basic components of the signal processing path, i.e., signal filtering, envelope detection, signal compression and scan conversion [Basoglu et  al., 1998], and in a second time review more recent considerations.

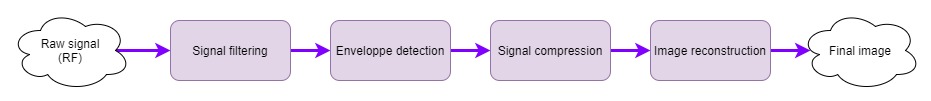


Figure 2: Block diagram the signal processing path

The signal processing step has one goal, that is to extract the right information from the raw electrical signal into an actionable information for the user.

Upstream, ***General filtering*** has been commonly used 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 [Assef et  al., 2019b, Levesque and Sawan, 2009], so to ensure a clean signal for further processing.

***Deconvolution*** as point source object is scanned with an ultrasound transducer, it will be not be represented as a sharp point but as a blurred smear. 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 [Jensen et  al., 1993, Dalitz et  al., 2015]. It establishes the possibility of recursively reconstructing the true position of the point source through deconvolution [Dalitz et  al., 2015].

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. Is 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 [Chang et  al., 2007, Assef et  al., 2019a, Assef et  al., 2018].

Once the image is assembled, ***Amplitude compression*** can be used to further reduce transfer rates needs between hardware and software, which are often a bottleneck. In this sense, having upstream compression would alleviate these bottlenecks [Soto-Cajiga et  al., 2012, Akkala et  al., 2014b]. Alternatives [Akkala et  al., 2014a, Boonleelakul et  al., 2013] 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.

***Image reconstruction*** is the last step to reconstruct a 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, called 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 et  al., 2019].

4.2 Recent signal processing considerations

It can be noted that element sensors (often focused as a given depth) have good characteristics to image around this region of depth. However, outside of this fixed depth, the resolution quickly degrades - which can can be alleviated by using ***Synthetic Aperture Focusing (SAF)*** [Andresen et  al., 2011, Assef et  al., 2015, LI et  al., 2018, Lewandowski et  al., 2012, Zhang et  al., 2016]. Other synthetic aperture techniques have been widely discussed, for example in [Romero-Laorden et  al., 2013, Jeon et  al., 2019] or earlier on [Burckhardt et  al., 1974]. Similarly, Monostatic Synthetic Aperture Scanner and Monostatic Fixed Focus Scanner are approaches worth citing in the review of data processing, as developed by [Bottenus et  al., 2015, Ylitalo and Ermert, 1994, Heuvel et  al., 2017, Nikolov et  al., 2008], aiming at improving images quality.

With an adaptation on the hardware side to accommodate shaped pulse sequences, it is possible to tap into barker code and compressed sensing techniques to increase image quality.

At the pulser stage, one can use ***barker codes*** to improve image resolution by shaping the excitation signal itself. It has been shown for example that it is possible to improve lateral resolution [Fujita and Hasegawa, 2017, Chun et  al., 2015, Kim et  al., 2018].

A more complex approach on the signal shaping and receiving is ***compressed sensing (CS)*** : traditional 2-D and 3D ultrasound require the use of complex sensors, with matching hardware such as cabling. There are available, still costly - but such sensors require more hardware and become ultimately more complex and expensive to produce. It appears that classical sampling is challenged by the signal processing "compressed sensing" field [Liutkus et  al., 2014, Hua et  al., 2011]. This allows for reconstruction of a signal with fewer samples than dictated by the Nyquist-Shannon sampling theorem. Starting with time reversal applications [Montaldo et  al., 2004, Montaldo et  al., 2005] or [Sarvazyan et  al., 2009], compressing measurements before sensing enable new ultrasound applications, where positioning a plastic coding mask in front of the aperture [Fedjajevs, 2016] or simply for the purpose of envelope extraction [Kim et  al., 2020]. One can therefore encode individual volume pixels or voxels using a ’chaotic’ medium [Luong et  al., 2016], allowing 3D imaging using a single-element ultrasound sensor and opening doors to simpler hardware and again new applications [Kruizinga et  al., 2017]. Different works have been dedicated to creating the phase encoding masks [van  der Meulen et  al., 2017] or even using random interference to improve image resolution [Ni and Lee, 2020].

From a transverse perspective, ***machine learning*** (ML) has shown promising improvement in terms of both image quality improvement [Wang et  al., 2019a, Hewener et  al., 2019] and support for image interpretation [Divya  Krishna et  al., 2016], even in A-mode [Brausch and Hewener, 2019]. An open-source MT tool to interpret Doppler signals [Dhutia et  al., 2017] has also been developed. ML also applies to texture imaging, as earlier proposed by reviewing "Average Higuchi Dimension of RF Time series" [Moradi et  al., 2006], or in to-non imaging techniques, such as mixing monitoring [Bowler et  al., 2020].

5 Conclusion

A review of state-of-the-art ultrasound hardware designs and implementation was presented in this article, opening on new challenges and considerations as ultrasound technologies are maturing and new approaches are made possible.

Though there was a lack of available open hardware on the market, there seems to be sufficient information available to assemble a proof-of-concept system that offers a safe, cheap and portable alternative to other imaging technologies, as demonstrated by the un0rick and lit3rick designs. More sophisticated systems will surely emerge from open designs, building on recent components and new controllers.

The number of more complex designs appears to have grown due to the increased availability of electronic components and AFE integration of additional analog channels, these systems also have improved functionality. However, these designs also require rapid logic control, which is today not easily possible from an open-source perspective. In addition, compressed sensing allows for drastic improvements in image quality while reducing the number of sensors and the corresponding hardware required.

From an academic perspective, there is significant evidence in the literature demonstrating the utility of open-source design, both from a medical perspective but also for private and public research purposes, not to mention education. Researchers have identified ultrasound as a safe, low-cost solution in medically under-served regions and markets with rising health costs. There is also increased interest in terms of private-sector research and development, as indicated by the abundance of recent works and new projects indicating the innovative aspects of the topic.

In general, open source ultrasound hardware research [Roman, 2019] has begun, and it is our hope that this article will encourage other researchers and makers to share their work.

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1. Lead of the un0rick.cc project [↑](#footnote-ref-2)