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

Luc Jonveaux[[1]](#footnote-3)1

Open-source hobbyist

Milly le Meugon, FR

kelu124@gmail.com

Carla Schloh

Fraunhofer MEVIS

Institute for Digital Medicine

Bremen, DE

carla.schloh@yahoo.de

William Meng

Stanford University

Stanford, CA, US

wlmeng@stanford.edu

Jorge Arija

MicroComp

Bilbao, ES

jarija@microcomp.es

Jean Rintoul

Mindseye Biomedical

London, UK

jean@mindseyebiomedical.com

19/06/2021

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 [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 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 [Wang et  al., 2020].

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., 2019d]. 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. It leverages progress in low-cost computing in order to offload functions which previously required complex and expensive hardware. From our community, we see users from college students to post-docs, on matters to non-destructive testing or medical imaging fields.

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], promote technology use, 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 will voluntarily discard the review of Doppler-related modes, including C-Mode, spectrogram and others, 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. We would deem M-Mode (as a A-Mode time motion display) an extension of the A-mode. 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] or later portable devices [Ligtvoet et  al., 1978], which would have to be able 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 5MHz, for a depth of up to 18cm

• 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

• 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, 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. 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]. New computing techniques for full wave imaging have also the opened door to better imaging [Guasch et  al., 2020, Rymarczyk et  al., 2019].

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Application | Description | References |  |
|  | 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, Zhang et  al., 2018a, Zhang et  al., 2021, Clementi et  al., 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. | [noa, , Carotenuto et  al., 2004, 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 et  al., 2011, Zhang et  al., 2017, Shomaji et  al., 2019, Joseph et  al., 2015a, Joseph et  al., 2015b, 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 et  al., 2017] | | \_ |
|  | Body monitoring | Tissue monitoring uses include tissue assessment, for example quantifying neuro-muscular disease progression. | [Keyes, 2017, Zhang, 2015, Brausch et  al., 2019, Park et  al., 2019] | | \_ |
|  | 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 support the follow-up of biofeedback, for example in stroke reeducation or human-machine interfaces. | [Sosnowska et  al., 2019, Sikdar et  al., 2014, Kwong et  al., 2020, Yang et  al., 2020, Li et  al., 2016, Boyd et  al., 2019, Eshky et  al., 2021] | | \_ |
|  | 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, Fernandes et  al., 2021] | | \_ |
|  | Neuromodulation | Ultrasound is used in neuromodulation experiments, including communication with implantable stimulators. | [Pashaei et  al., 2020, Johnson et  al., 2018, Seo et  al., 2016, Santagati et  al., 2020]. | | \_ |
|  | 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] | | \_ |
|  | 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, Yang et  al., 2019]. | | \_ |

Table 1: Applications, by group of uses

## 3 Considerations leading to the design of the system architecture

### 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, 2019b], 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 [Schuette et  al., 1976, Eggleton and Johnston, 1975, Skolnick and Matzuk, 1978], 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, we considered features provided by suppliers of research equipment, such as Verasonics, Olympus, Optel or Lecoeur Electronique.

### 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].

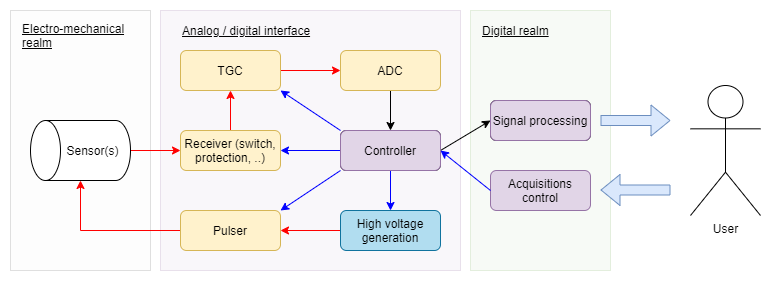


Figure 1: Block diagram of a general ultrasound system. Analog components are in yellow, digital in purple, and high voltage in blue.

The blocks consists in a Pulser, creating 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 needs to be coordination these different aspects in parallel, which is the reason for the choice of FPGAs over microcontrollers. Once digitized, the signal is exported to the user.

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.

As the sensors are mostly analog, and because of the low signals they yield, special care must be put on the analog parts (in yellow in 1) so that a satisfactory analog signal is extracted before digitization.

### 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. Most of these systems were design for academic research, and are not put to market. Both simple and high-end systems were considered in this review, as it is possible to exploit aspects of their design approach for use on simpler platforms.

The objective of this review is not to design a single device, but to provide with an overview of the current state of art, and provide a benchmark for further specifications. The design of specific hardware, using only part of this review, would be a separate research topic.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **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., 2019b] | 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

From these designs, as volumes are not specified, it may be possible to guess the cost of components, but searching for a comparative cost would not yield relevant information.

#### 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,STHV748, LM96551 | [Martins, 2017, Zhang et  al., 2017, Hewener et  al., 2012, Worthing, 2016, Joseph et  al., 2015b] |
| 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 [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, 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 Time Gain Compensation (TGC) 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]. AD604 [Yang et  al., 2019], a dual variable amplifier with a gain of 48dB, was also considered.

#### 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. In simple design, mono-frequency sensors from 1MHz to 15MHz are used, sometimes with higher frequencies, though multi-frequencies [Sun et  al., 2018] devices have also been developed [Lukacs et  al., 1998, Foster et  al., 2009]. In some cases, FIFO buffers between the ADC and the controler were used [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 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, Seo, 2018, Sabbella, 2021].

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., 2013]. High-voltage design for ultrasound has been a particular point of interest. The 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]. Devices such as the LM96550 were not considered in this review because of their relative important physical size. In the open-source literature, designs used of an expensive RECOM device, providing a 0 - 120V range, or a NMT0572SC, providing 24, 48 and 72V rails, as well as the LT3494 with a rail up to 39V. Other alternatives were considered, namely the *MAX668* (which operates from O to 150V), *MAX1856* (between -80V and -24V), an *MIC3172* design, using an *HV9150* to reach up to 200V, or a *MAX15031* of up to 80V. The *DRV8662* family, including the DRV2700, also has been used to provide rails for up to 105V. Older devices were seen using integrated devices, such as the PICO 5SM250S DC-DC.

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 [Shaw, 1977, Matzuk and Skolnick, 1978, Wilkinson, 1981], 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 [Holm et  al., 1975], 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, ... ) [Jonveaux, 2019a]. This approach was initially more commonly seen in intra-cavity probes, due to space constraints [Hisanaga et  al., 1980].

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]. Alternatively, the use of mobile acoustic mirrors with fixed transducers was considered [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, 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, Govindan et  al., 2013b], which allows the system’s 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., 2019c, 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 (TPX), which can be used for example on high-frequency ultrasound scanners [Erickson et  al., 2001, Brown et  al., 2013], or perspex [Bow et  al., 1979]. 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], but also through Ethernet as well (eg with a CP2200) or WiFi.

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 [Gilliland et  al., 2016, Govindan et  al., 2013a]. 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, 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 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.

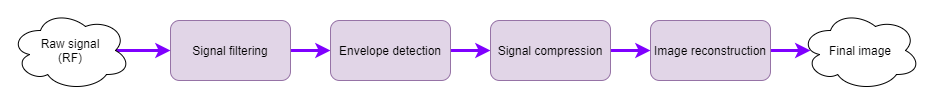


Figure 2: Block diagram the signal processing path

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.

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].

At this stage, and for B-Mode imaging, ***deconvolution*** can be used to remove the usual blur of a single point image, due to the transducer geometry.Knowing a system’s PSF makes improving the image resolution an inverse problem [Jensen et  al., 1993, Dalitz et  al., 2015], and establishes the possibility of recursively reconstructing the true position and shape of the point through deconvolution [Dalitz et  al., 2015].

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.

At the pulser stage, one can use ***barker codes*** [Zhang et  al., 2019a, Wang et  al., 2021] to improve image resolution by shaping the excitation signal itself [Isla and Cegla, 2017]. It has been shown for example that it is possible to improve lateral as well as axial 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 channel 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.

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

In general, open source ultrasound hardware research [Roman, 2019] is accelerating, and it is our hope that this article will encourage other researchers, manufacturers [Yu et  al., 2020] and makers to share their work.

## Acknowledgment

The main author would like to thank the co-authors for their contributions and express appreciation to the Open Ultrasound Society for their insights and exchanges on [Slack](https://join.slack.com/t/usdevkit/shared_invite/zt-2g501obl-z53YHyGOOMZjeCXuXzjZow). Special thanks to David, Vladimir, Andrew, Bogdan, and Ahmed.

## Supplementary information

Equipment providers 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., 2018b, Al-Aufi et  al., 2019],

• MKC [Park et  al., 2019],

• 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].

References

[noa, ] Wrist and Finger Gesture Recognition With Single-Element Ultrasound Signals: A Comparison With Single-Channel Surface Electromyogram - IEEE Journals & Magazine.

[Ahn et  al., 2015] Ahn, S., Kang, J., Kim, P., Lee, G., Jeong, E., Jung, W., Park, M., and Song, T. k. (2015). Smartphone-based portable ultrasound imaging system: Prototype implementation and evaluation. In *2015 IEEE International Ultrasonics Symposium (IUS)*, pages 1–4.

[Akkala et  al., 2014a] Akkala, V., Bharath, R., Rajalakshmi, P., and Kumar, P. (2014a). Compression techniques for IoT enabled handheld ultrasound imaging system. In *2014 IEEE Conference on Biomedical Engineering and Sciences (IECBES)*, pages 648–652.

[Akkala et  al., 2014b] Akkala, V., Rajalakshmi, P., Kumar, P., and Desai, U. B. (2014b). FPGA based ultrasound backend system with image enhancement technique. In *5th ISSNIP-IEEE Biosignals and Biorobotics Conference (2014): Biosignals and Robotics for Better and Safer Living (BRC)*, pages 1–5.

[Al-Aufi et  al., 2019] Al-Aufi, Y. A., Hewakandamby, B. N., Dimitrakis, G., Holmes, M., Hasan, A., and Watson, N. J. (2019). Thin film thickness measurements in two phase annular flows using ultrasonic pulse echo techniques. *Flow Measurement and Instrumentation*, 66:67–78.

[Ali, 2008] Ali, M. (2008). Signal processing overview of ultrasound systems for medical imaging.

[Alqasemi et  al., 2012] Alqasemi, U., Li, H., Aguirre, A., and Zhu, Q. (2012). FPGA-Based Reconfigurable Processor for Ultrafast Interlaced Ultrasound and Photoacoustic Imaging. *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, 59(7):1344–1353.

[Andresen et  al., 2011] Andresen, H., Nikolov, S. I., and Jensen, J. A. (2011). Synthetic aperture focusing for a single-element transducer undergoing helical motion. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 58(5):935–943.

[Ashfaq and Ermert, 2004] Ashfaq, M. and Ermert, H. (2004). A new approach towards ultrasonic transmission tomography with a standard ultrasound system. In *IEEE Ultrasonics Symposium, 2004*, volume 3, pages 1848–1851 Vol.3. ISSN: 1051-0117.

[Assef et  al., 2019a] Assef, A. A., de Oliveira, J., Maia, J. M., and Costa, E. T. (2019a). FPGA Implementation and Evaluation of an Approximate Hilbert Transform-Based Envelope Detector for Ultrasound Imaging Using the DSP Builder Development Tool. In *2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pages 2813–2816. ISSN: 1557-170X.

[Assef et  al., 2018] Assef, A. A., Ferreira, B. M., Maia, J. M., and Costa, E. T. (2018). Modeling and FPGA-based implementation of an efficient and simple envelope detector using a Hilbert Transform FIR filter for ultrasound imaging applications. *Research on Biomedical Engineering*, 34(1):87–92.

[Assef et  al., 2015] Assef, A. A., Maia, J. M., and Costa, E. T. (2015). A flexible multichannel FPGA and PC-Based ultrasound system for medical imaging research: initial phantom experiments. *Research on Biomedical Engineering*, 31(3):277–281.

[Assef et  al., 2016] Assef, A. A., Maia, J. M., and Costa, E. T. (2016). Initial experiments of a 128-channel FPGA and PC-based ultrasound imaging system for teaching and research activities. In *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pages 5172–5175.

[Assef et  al., 2014] Assef, A. A., Maia, J. M., Costa, E. T., and Nantes, V. L. d. S. (2014). A compact and reconfigurable 8-channel Ultrasound Evaluation System for experimental research. In *2014 IEEE International Ultrasonics Symposium*, pages 1607–1610.

[Assef et  al., 2012] Assef, A. A., Maia, J. M., Schneider, F. K., Costa, E. T., and Button, V. L. S. N. (2012). Design of a 128-channel FPGA-based ultrasound imaging beamformer for research activities. pages 635–638. IEEE.

[Assef et  al., 2019b] Assef, A. A., Oliveira, J. d., Scherbaty, L., Maia, J. M., Zimbico, A., Ferreira, B. M., and Costa, E. T. (2019b). Modeling of a Simple and Efficient Cascaded FPGA-Based Digital Band-Pass FIR Filter for Raw Ultrasound Data. *XXVI Brazilian Congress on Biomedical Engineering*, pages 501–505.

[Attarzadeh et  al., 2017] Attarzadeh, H., Xu, Y., and Ytterdal, T. (2017). A Low-Power High-Dynamic-Range Receiver System for In-Probe 3-D Ultrasonic Imaging. *IEEE Transactions on Biomedical Circuits and Systems*, 11(5):1053–1064.

[Basak et  al., 2013] Basak, A., Ranganathan, V., and Bhunia, S. (2013). A wearable ultrasonic assembly for point-of-care autonomous diagnostics of malignant growth. pages 128–131.

[Basoglu et  al., 1998] Basoglu, C., Managuli, R., York, G., and Kim, Y. (1998). Computing requirements of modern medical diagnostic ultrasound machines. *Parallel Computing*, 24(9):1407–1431.

[Batbayar et  al., 2018] Batbayar, E., Ham, W., Tumenjargal, E., and Song, C. (2018). A Hardware Design of Capture Multichannel Ultrasound Raw Signal for Photoacoustic Medical Image. *제어로봇시스템학회 국내학술대회 논문집*, pages 257–259.

[Bezanson et  al., 2011] Bezanson, A. B., Adamson, R., and Brown, J. A. (2011). A low-cost high frame-rate piezoelectric scanning mechanism for high-frequency ultrasound systems. In *2011 IEEE International Ultrasonics Symposium*, pages 458–461.

[Bharath et  al., 2015a] Bharath, R., Chandrashekar, D., Akkala, V., Krishna, D., Ponduri, H., Rajalakshmi, P., and Desai, U. B. (2015a). Portable ultrasound scanner for remote diagnosis. In *2015 17th International Conference on E-health Networking, Application Services (HealthCom)*, pages 211–216.

[Bharath et  al., 2015b] Bharath, R., Kumar, P., Dusa, C., Akkala, V., Puli, S., Ponduri, H., Krishna, K. D., Rajalakshmi, P., Merchant, S. N., Mateen, M. A., and Desai, U. B. (2015b). FPGA-Based Portable Ultrasound Scanning System with Automatic Kidney Detection. *Journal of Imaging*, 1(1):193–219.

[Bharath et  al., 2018] Bharath, R., Kumar, P., Reddy, D. S., and Rajalakshmi, P. (2018). Compact and Programmable Ultrasound Front-End Processing Module for Research Activities. In *2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pages 921–924, Honolulu, HI. IEEE.

[Bharath et  al., 2016] Bharath, R., Reddy, D. S., Kumar, P., and Rajalakshmi, P. (2016). Novel architecture for wireless transducer based ultrasound imaging system. In *2016 IEEE EMBS Conference on Biomedical Engineering and Sciences (IECBES)*, pages 432–436.

[Biosono, ] Biosono. SonoLab Echo I hardware.

[Boni et  al., 2016] Boni, E., Bassi, L., Dallai, A., Guidi, F., Meacci, V., Ramalli, A., Ricci, S., and Tortoli, P. (2016). ULA-OP 256: A 256-Channel Open Scanner for Development and Real-Time Implementation of New Ultrasound Methods. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 63(10):1488–1495.

[Boni et  al., 2012] Boni, E., Bassi, L., Dallai, A., Guidi, F., Ramalli, A., Ricci, S., Housden, J., and Tortoli, P. (2012). A reconfigurable and programmable FPGA-based system for nonstandard ultrasound methods. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 59(7):1378–1385.

[Boni et  al., 2018] Boni, E., Yu, A. C. H., Freear, S., Jensen, J. A., and Tortoli, P. (2018). Ultrasound Open Platforms for Next-Generation Imaging Technique Development. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 65(7):1078–1092.

[Boonleelakul et  al., 2013] Boonleelakul, W., Techavipoo, U., Worasawate, D., Keinprasit, R., Pinunsottikul, P., Sugino, N., and Thajchayapong, P. (2013). Compression of ultrasound RF data using quantization and decimation. In *The 6th 2013 Biomedical Engineering International Conference*, pages 1–4.

[Bottenus et  al., 2015] Bottenus, N., Jakovljevic, M., Boctor, E., and E. Trahey, G. (2015). Implementation of swept synthetic aperture imaging. *Progress in Biomedical Optics and Imaging - Proceedings of SPIE*, 9419.

[Bottenus et  al., 2016] Bottenus, N., Long, W., Zhang, H. K., Jakovljevic, M., Bradway, D. P., Boctor, E. M., and Trahey, G. E. (2016). Feasibility of Swept Synthetic Aperture Ultrasound Imaging. *IEEE Transactions on Medical Imaging*, 35(7):1676–1685.

[Bow et  al., 1979] Bow, C. R., McDicken, W. N., Anderson, T., Scorgie, R. E., and Muir, A. L. (1979). A rotating transducer real-time scanner for ultrasonic examination of the heart and abdomen. *The British Journal of Radiology*, 52(613):29–33.

[Bowler et  al., 2020] Bowler, A. L., Bakalis, S., and Watson, N. J. (2020). Monitoring Mixing Processes Using Ultrasonic Sensors and Machine Learning. *Sensors*, 20(7):1813.

[Boyd et  al., 2019] Boyd, P., Fang, Y., and Liu, H. (2019). Ultrasound Feature Evaluation for Robustness to Sensor Shift in Ultrasound Sensor Based Hand Motion Recognition. In Althoefer, K., Konstantinova, J., and Zhang, K., editors,  *Towards Autonomous Robotic Systems*, Lecture Notes in Computer Science, pages 115–125, Cham. Springer International Publishing.

[Brausch and Hewener, 2019] Brausch, L. and Hewener, H. (2019). Classifying muscle states with ultrasonic single element transducer data using machine learning strategies. page 022001, Bruges, Belgium.

[Brausch et  al., 2019] Brausch, L., Hewener, H., and Lukowicz, P. (2019). Towards a wearable low-cost ultrasound device for classification of muscle activity and muscle fatigue. In *Proceedings of the 23rd International Symposium on Wearable Computers - ISWC ’19*, pages 20–22, London, United Kingdom. ACM Press.

[Brown et  al., 2013] Brown, J. A., Leadbetter, J., Leung, M., Bezanson, A., and Adamson, R. (2013). A low cost open source high frame-rate high-frequency imaging system. In *2013 IEEE International Ultrasonics Symposium (IUS)*, pages 549–552.

[Brown and Lockwood, 2002] Brown, J. A. and Lockwood, G. R. (2002). Low-cost, high-performance pulse generator for ultrasound imaging. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 49(6):848–851.

[Brunner and Com, 2002] Brunner, E. and Com, E. (2002). How ultrasound system considerations influence front-end component choice.

[Burckhardt et  al., 1974] Burckhardt, C. E., Grandchamp, P. A., and Hoffmann, H. (1974). An Experimental 2 MHz Synthetic Aperture Sonar System Intended for Medical Use. *IEEE Transactions on Sonics and Ultrasonics*, 21(1):1–6.

[Carotenuto et  al., 2004] Carotenuto, R., Caliano, G., and Caronti, A. (2004). Very fast scanning probe for ophthalmic echography using an ultrasound motor. In *IEEE Ultrasonics Symposium, 2004*, volume 2, pages 1310–1313 Vol.2.

[Carotenuto et  al., 2005] Carotenuto, R., Caliano, G., Caronti, A., Savoia, A., and Pappalardo, M. (2005). Fast scanning probe for ophthalmic echography using an ultrasound motor. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 52(11):2039–2046.

[Chang et  al., 2007] Chang, J., Yen, J., and Shung, K. (2007). A Novel Envelope Detector for High-Frame Rate, High-Frequency Ultrasound Imaging. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 54(9):1792–1801.

[Chang et  al., 2009] Chang, J. H., Sun, L., Yen, J. T., and Shung, K. K. (2009). Low-Cost, High-Speed Back-End Processing System for High-Frequency Ultrasound B-Mode Imaging. *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, 56(7):1490–1497.

[Chang-hong Hu et  al., 2008] Chang-hong Hu, Qifa Zhou, and Shung, K. (2008). Design and implementation of high frequency ultrasound pulsed-wave Doppler using FPGA. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 55(9):2109–2111.

[Chatar and George, 2016] Chatar, K. and George, M. L. (2016). Analysis of Existing Designs for FPGA-Based Ultrasound Imaging Systems. *International Journal of Signal Processing, Image Processing and Pattern Recognition*, 9(7):13–24.

[Chen et  al., 2016] Chen, C.-K., Fang, J., Wan, Y.-L., and Tsui, P.-H. (2016). Ultrasound characterization of the mastoid for detecting middle ear effusion: A preliminary clinical validation. *Scientific Reports*, 6(1):27777. Number: 1 Publisher: Nature Publishing Group.

[Cheung et  al., 2012] Cheung, C. C. P., Yu, A. C. H., Salimi, N., Yiu, B. Y. S., Tsang, I. K. H., Kerby, B., Azar, R. Z., and Dickie, K. (2012). Multi-channel pre-beamformed data acquisition system for research on advanced ultrasound imaging methods. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 59(2):243–253.

[Choi et  al., 2020] Choi, S., Kim, J. Y., Lim, H. G., Baik, J. W., Kim, H. H., and Kim, C. (2020). Versatile Single-Element Ultrasound Imaging Platform using a Water-Proofed MEMS Scanner for Animals and Humans. *Scientific Reports*, 10(1):6544.

[Chu, ] Chu, C. Designing An Ultrasound Pulser with MD1812/MD1813 Composite Drivers.

[Chun et  al., 2015] Chun, G.-C., Chiang, H.-J., Lin, K.-H., Li, C.-M., Chen, P.-J., and Chen, T. (2015). Ultrasound Elasticity Imaging System with Chirp-Coded Excitation for Assessing Biomechanical Properties of Elasticity Phantom. *Materials*, 8(12):8392–8413. Number: 12 Publisher: Multidisciplinary Digital Publishing Institute.

[Clementi et  al., 2020] Clementi, C., Littmann, F., and Capineri, L. (2020). Identification and Authentication of Copper Canisters for Spent Nuclear Fuel by a Portable Ultrasonic System. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 67(8):1667–1678.

[Cox et  al., 2017] Cox, B. F., Stewart, F., Lay, H., Cummins, G., Newton, I. P., Desmulliez, M. P. Y., Steele, R. J. C., Näthke, I., and Cochran, S. (2017). Ultrasound capsule endoscopy: sounding out the future. *Annals of Translational Medicine*, 5(9):201.

[Cramer et  al., 2015] Cramer, K. E., Perey, D. F., and Yost, W. T. (2015). Ultrasonic inspection to quantify failure pathologies of crimped electrical connections. *AIP Conference Proceedings*, 1650(1):1820–1825. Publisher: American Institute of Physics.

[Csány et  al., 2019] Csány, G., Szalai, K., and Gyöngy, M. (2019). A real-time data-based scan conversion method for single element ultrasound transducers. *Ultrasonics*, 93:26–36.

[Dalitz et  al., 2015] Dalitz, C., Pohle-Frohlich, R., and Michalk, T. (2015). Point spread functions and deconvolution of ultrasonic images. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 62(3):531–544.

[Dhutia et  al., 2017] Dhutia, N. M., Zolgharni, M., Mielewczik, M., Negoita, M., Sacchi, S., Manoharan, K., Francis, D. P., and Cole, G. D. (2017). Open-source, vendor-independent, automated multi-beat tissue Doppler echocardiography analysis. *The International Journal of Cardiovascular Imaging*, 33(8):1135–1148.

[Di  Ianni et  al., 2016] Di Ianni, T., Hemmsen, M. C., Llimos Muntal, P., Jorgensen, I. H. H., and Jensen, J. A. (2016). System-Level Design of an Integrated Receiver Front End for a Wireless Ultrasound Probe. *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, 63(11):1935–1946.

[Divya  Krishna et  al., 2016] Divya Krishna, K., Akkala, V., Bharath, R., Rajalakshmi, P., Mohammed, A. M., Merchant, S. N., and Desai, U. B. (2016). Computer Aided Abnormality Detection for Kidney on FPGA Based IoT Enabled Portable Ultrasound Imaging System. *IRBM*, 37(4):189–197.

[Duric et  al., 2007] Duric, N., Littrup, P., Poulo, L., Babkin, A., Pevzner, R., Holsapple, E., Rama, O., and Glide, C. (2007). Detection of breast cancer with ultrasound tomography: first results with the Computed Ultrasound Risk Evaluation (CURE) prototype. *Medical Physics*, 34(2):773–785.

[Dusa et  al., 2014] Dusa, C., Rajalakshmi, P., Puli, S., Desai, U. B., and Merchant, S. N. (2014). Low complex, programmable FPGA based 8-channel ultrasound transmitter for medical imaging researches. In *2014 IEEE 16th International Conference on e-Health Networking, Applications and Services (Healthcom)*, pages 252–256.

[Eggleton and Johnston, 1975] Eggleton, R. C. and Johnston, K. W. (1975). Real Time B-Mode Mechanical Scanning System. pages 96–100, Kansas City.

[Erickson et  al., 2001] Erickson, S., Kruse, D., and Ferrara, K. (2001). A hand-held, high frequency ultrasound scanner. In *2001 IEEE Ultrasonics Symposium. Proceedings. An International Symposium (Cat. No.01CH37263)*, volume 2, pages 1465–1468 vol.2.

[Eshky et  al., 2021] Eshky, A., Cleland, J., Ribeiro, M. S., Sugden, E., Richmond, K., and Renals, S. (2021). Automatic audiovisual synchronisation for ultrasound tongue imaging. *Speech Communication*, 132:83–95.

[Farsoni et  al., 2017] Farsoni, S., Bonfè, M., and Astolfi, L. (2017). A low-cost high-fidelity ultrasound simulator with the inertial tracking of the probe pose. *Control Engineering Practice*, 59:183–193.

[Fedjajevs, 2016] Fedjajevs (2016). *Ultrasound Imaging Using a Single Element Transducer*. PhD thesis, tudelft.

[Fernandes et  al., 2021] Fernandes, A. J., Ono, Y., and Ukwatta, E. (2021). Evaluation of Finger Flexion Classification at Reduced Lateral Spatial Resolutions of Ultrasound. *IEEE Access*, 9:24105–24118. Conference Name: IEEE Access.

[Fontes-Pereira et  al., 2018] Fontes-Pereira, A., Rosa, P., Barboza, T., Matusin, D., Freire, A. S., Braz, B. F., Machado, C. B., von Krüger, M. A., Souza, S. A. L. d., Santelli, R. E., and Pereira, W. C. d. A. (2018). Monitoring bone changes due to calcium, magnesium, and phosphorus loss in rat femurs using Quantitative Ultrasound. *Scientific Reports*, 8(1):1–9.

[Foster et  al., 2009] Foster, F. S., Mehi, J., Lukacs, M., Hirson, D., White, C., Chaggares, C., and Needles, A. (2009). A New 15–50 MHz Array-Based Micro-Ultrasound Scanner for Preclinical Imaging. *Ultrasound in Medicine & Biology*, 35(10):1700–1708.

[FRITSCH, ] FRITSCH, C. A Full Featured Ultrasound NDE System in a Standard FPGA.

[Fujita and Hasegawa, 2017] Fujita, H. and Hasegawa, H. (2017). Effect of frequency characteristic of excitation pulse on lateral spatial resolution in coded ultrasound imaging. *Japanese Journal of Applied Physics*, 56(7S1):07JF16.

[Garcia, 2014] Garcia, J. E. (2014). *Piezoelectric transducer built-in self-test for logging while drilling instrument sensor evaluation at rig site*. Thesis.

[Garcia-Rodriguez et  al., 2010] Garcia-Rodriguez, M., Garcia-Alvarez, J., Yañez, Y., Garcia-Hernandez, M., Salazar, J., Turo, A., and Chavez, J. (2010). Low cost matching network for ultrasonic transducers. *Physics Procedia*, 3(1):1025–1031.

[Gemmeke et  al., 2010] Gemmeke, H., Berger, L., Birk, M., Göbel, G., Menshikov, A., Tcherniakhovski, D., Zapf, M., and Ruiter, N. V. (2010). Hardware setup for the next generation of 3D Ultrasound Computer Tomography. In *IEEE Nuclear Science Symposuim Medical Imaging Conference*, pages 2449–2454. ISSN: 1082-3654.

[George et  al., 2018] George, S. S., Huang, M. C., and Ignjatovic, Z. (2018). Portable ultrasound imaging system with super-resolution capabilities. *Ultrasonics*.

[Gibney, 2016] Gibney, E. (2016). ‘Open-hardware’ pioneers push for low-cost lab kit. *Nature*, 531(7593):147–148.

[Gil-Alba et  al., 2019] Gil-Alba, R., Alonso, L., Navarro, C., and García-Castillo, S. K. (2019). Morphological study of damage evolution in woven-laminates subjected to high-velocity impact. *Mechanics of Advanced Materials and Structures*, 26(24):2023–2029.

[Gilliland et  al., 2016] Gilliland, S., Govindan, P., and Saniie, J. (2016). Architecture of the reconfigurable ultrasonic system-on-chip hardware platform. *IET Circuits, Devices & Systems*, 10(4):301–308.

[Govindan et  al., 2013a] Govindan, P., Gilliland, S., Gonnot, T., and Saniie, J. (2013a). HW/SW co-design for reconfigurable Ultrasonic System-on-Chip platform. In *IEEE International Conference on Electro-Information Technology , EIT 2013*, pages 1–4. ISSN: 2154-0373.

[Govindan et  al., 2013b] Govindan, P., Gilliland, S., Kasaeifard, A., Gonnot, T., and Saniie, J. (2013b). Performance analysis of reconfigurable ultrasonic system-on-chip hardware platform. In *2013 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, pages 1550–1553. ISSN: 1091-5281.

[Govindan et  al., 2015] Govindan, P., Vasudevan, V., Gonnot, T., and Saniie, J. (2015). Reconfigurable Ultrasonic Testing System Development Using Programmable Analog Front-End and Reconfigurable System-on-Chip Hardware. *Circuits and Systems*, 06(07):161.

[GoŃabek et  al., 2019] Gołąbek, M., Rymarczyk, T., and Adamkiewicz, P. (2019). Construction of Ultrasonic Reflection Tomograph for Analysis of Technological Processes. In *2019 Applications of Electromagnetics in Modern Engineering and Medicine (PTZE)*, pages 47–51.

[Granata et  al., 2020] Granata, E., Vishwa, A., and Shen, J. (2020). Designing Bipolar High Voltage SEPIC Supply for Ultrasound Smart Probe. page 15.

[Gräsel et  al., 2017] Gräsel, M., Glüer, C. C., and Barkmann, R. (2017). Characterization of a new ultrasound device designed for measuring cortical porosity at the human tibia: A phantom study. *Ultrasonics*, 76:183–191.

[Guasch et  al., 2020] Guasch, L., Calderón Agudo, O., Tang, M.-X., Nachev, P., and Warner, M. (2020). Full-waveform inversion imaging of the human brain. *npj Digital Medicine*, 3(1):1–12.

[Gwirc et  al., 2019] Gwirc, S. N., Márquez, M. A., Mariño, N., Pascoli, H., and Fernández, N. (2019). Desarrollo de Módulo Emisor/Receptor Ultrasónico Multicanal. Accepted: 2019-10-24T15:56:08Z Publisher: Universidad Nacional de La Matanza. Departamento de Ingeniería e Investigaciones Tecnológicas.

[Hager, 2019] Hager, P. A. (2019). *Design of Fully-Digital Medical Ultrasound Imaging Systems*. PhD thesis, Zurich.

[Hager and Benini, 2019] Hager, P. A. and Benini, L. (2019). LightProbe: A Digital Ultrasound Probe for Software-Defined Ultrafast Imaging. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 66(4):747–760.

[Hager et  al., 2017a] Hager, P. A., Risser, C., Weber, P. K., and Benini, L. (2017a). LightProbe: A 64-channel programmable ultrasound transducer head with an integrated front-end and a 26.4 Gb/s optical link. In *2017 IEEE International Symposium on Circuits and Systems (ISCAS)*, pages 1–4.

[Hager et  al., 2017b] Hager, P. A., Speicher, D., Degel, C., and Benini, L. (2017b). UltraLight: An ultrafast imaging platform based on a digital 64-channel ultrasound probe. pages 1–5. IEEE.

[Havlice and Taenzer, 1979] Havlice, J. F. and Taenzer, J. C. (1979). Medical ultrasonic imaging: An overview of principles and instrumentation. *Proceedings of the IEEE*, 67(4):620–641.

[Herickhoff et  al., 2019] Herickhoff, C., Lin, J., and Dahl, J. (2019). Low-cost Sensor-enabled Freehand 3D Ultrasound. In *2019 IEEE International Ultrasonics Symposium (IUS)*, pages 498–501. ISSN: 1948-5727.

[Herickhoff et  al., 2018] Herickhoff, C. D., Morgan, M. R., Broder, J. S., and Dahl, J. J. (2018). Low-cost Volumetric Ultrasound by Augmentation of 2D Systems: Design and Prototype. *Ultrasonic Imaging*, 40(1):35–48.

[Heuvel et  al., 2017] Heuvel, T. L. A. v. d., Graham, D. J., Smith, K. J., Korte, C. L. d., and Neasham, J. A. (2017). Development of a Low-Cost Medical Ultrasound Scanner Using a Monostatic Synthetic Aperture. *IEEE Transactions on Biomedical Circuits and Systems*, 11(4):849–857.

[Hewener et  al., 2019] Hewener, H., Risser, C., Brausch, L., Rohrer, T., and Tretbar, S. (2019). A mobile ultrasound system for majority detection. In *2019 IEEE International Ultrasonics Symposium (IUS)*, pages 502–505. ISSN: 1948-5719.

[Hewener et  al., 2012] Hewener, H. J., Welsch, H. J., Fonfara, H., Motzki, F., and Tretbar, S. H. (2012). Highly scalable and flexible FPGA based platform for advanced ultrasound research. In *2012 IEEE International Ultrasonics Symposium*, pages 2075–2080.

[Hidayat et  al., 2020] Hidayat, D., Syafei, N. S., Emiliano, Rohadi, N., Setianto, and Wibawa, B. M. (2020). Determination of generated ultrasonic wave characteristics by a bipolar square burst excitation. *Journal of Physics: Conference Series*, 1568:012007.

[HILLGER, 2016] HILLGER, W. (2016). High Frequency Ultrasonic Systems with Frequency Ranges of 35 to 200 MHz.

[Hisanaga et  al., 1980] Hisanaga, K., Hisanaga, A., Hibi, N., Nishimura, K., and Kambe, T. (1980). High Speed Rotating Scanner for Transesophageal Cross-Sectional Echocardiography. *The American Journal of Cardiology*, 46(5):837–842.

[Holm et  al., 1975] Holm, H. H., Kristensen, J. K., Pedersen, J. F., Hancke, S., and Northeved, A. (1975). A new mechanical real time ultrasonic contact scanner. *Ultrasound in Medicine & Biology*, 2(1):19–23.

[Hu et  al., 2011] Hu, T., Zhao, X., and Xia, L. (2011). Design of a protable ultrasonic system based on USB used in carotid artery measurement. In *2011 4th International Conference on Biomedical Engineering and Informatics (BMEI)*, volume 2, pages 1068–1071. ISSN: 1948-2922.

[Hua et  al., 2011] Hua, S., Yuchi, M., and Ding, M. (2011). Compressed Sensing for RF Signal Reconstruction in B-model Ultrasound Imaging. In *2011 International Conference on Intelligent Computation and Bio-Medical Instrumentation*, pages 19–22.

[Huang and Zou, 2015] Huang, C.-H. and Zou, J. (2015). A novel two-axis micromechanical scanning transducer using water-immersible electromagnetic actuators for handheld 3D ultrasound imaging. *Sensors and Actuators A: Physical*, 236:281–288.

[Ibrahim et  al., 2017] Ibrahim, A., Simon, W., Doy, D., Pignat, E., Angiolini, F., Arditi, M., Thiran, J. P., and Micheli, G. D. (2017). Single-FPGA complete 3D and 2D medical ultrasound imager. In *2017 Conference on Design and Architectures for Signal and Image Processing (DASIP)*, pages 1–6.

[Ibrahim et  al., 2018] Ibrahim, A., Zhang, S., Angiolini, F., Arditi, M., Kimura, S., Goto, S., Thiran, J., and Micheli, G. D. (2018). Towards Ultrasound Everywhere: A Portable 3D Digital Back-End Capable of Zone and Compound Imaging. *IEEE Transactions on Biomedical Circuits and Systems*, pages 1–14.

[Isla and Cegla, 2017] Isla, J. and Cegla, FCoded Excitation for Pulse-Echo Systems. *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, 64(4):736–748.

[Jensen et  al., 1993] Jensen, J. A., Mathorne, J., Gravesen, T., and Stage, B. (1993). Deconvolution of in-Vivo Ultrasound B-Mode Images , Deconvolution of in-Vivo Ultrasound B-Mode Images. *Ultrasonic Imaging*, 15(2):122–133.

[Jeon et  al., 2019] Jeon, S., Park, J., Managuli, R., and Kim, C. (2019). A Novel 2-D Synthetic Aperture Focusing Technique for Acoustic-Resolution Photoacoustic Microscopy. *IEEE Transactions on Medical Imaging*, 38(1):250–260.

[Jin et  al., 2017] Jin, B. C., Li, X., Jain, A., González, C., LLorca, J., and Nutt, S. (2017). Optimization of microstructures and mechanical properties of composite oriented strand board from reused prepreg. *Composite Structures*, 174:389–398.

[Johnson et  al., 2018] Johnson, B. C., Shen, K., Piech, D., Ghanbari, M. M., Li, K. Y., Neely, R., Carmena, J. M., Maharbiz, M. M., and Muller, R. (2018). StimDust: A 6.5mm3, wireless ultrasonic peripheral nerve stimulator with 82% peak chip efficiency. In *2018 IEEE Custom Integrated Circuits Conference (CICC)*, pages 1–4. ISSN: 2152-3630.

[Jonveaux, 2017] Jonveaux, L. (2017). Arduino-like development kit for single-element ultrasound imaging. *Journal of Open Hardware*, 1(1).

[Jonveaux, 2019a] Jonveaux, L. (2019a). Review of mechanical probes.

[Jonveaux, 2019b] Jonveaux, L. (2019b). un0rick : open-source fpga board for single element ultrasound imaging.

[Joseph et  al., 2015a] Joseph, J., Radhakrishnan, R., Kusmakar, S., Thrivikraman, A. S., and Sivaprakasam, M. (2015a). Technical Validation of ARTSENS–An Image Free Device for Evaluation of Vascular Stiffness. *IEEE Journal of Translational Engineering in Health and Medicine*, 3:1–13.

[Joseph et  al., 2015b] Joseph, J., Thrivikraman, A. S., Radhakrishnan, R., and Sivaprakasam, M. (2015b). ARTSENSTouch - A portable device for evaluation of carotid artery stiffness. In *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pages 3755–3758.

[Kang et  al., 2017] Kang, J., Kim, Y., Lee, W., and Yoo, Y. (2017). A New Dynamic Complex Baseband Pulse Compression Method for Chirp-Coded Excitation in Medical Ultrasound Imaging. *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, 64(11):1698–1710.

[Karjalainen et  al., 2012] Karjalainen, J. P., Riekkinen, O., Töyräs, J., Hakulinen, M., Kröger, H., Rikkonen, T., Salovaara, K., and Jurvelin, J. S. (2012). Multi-site bone ultrasound measurements in elderly women with and without previous hip fractures. *Osteoporosis International*, 23(4):1287–1295.

[Keyes, 2017] Keyes, S. R. (2017). *Electrical system for interfacing with muscle for use in prosthetic devices*. Thesis, Massachusetts Institute of Technology.

[Kidav et  al., 2019] Kidav, J. U., Sivamangai, N. M., Pillai, M. P., and Raja M, S. (2019). Architecture and FPGA prototype of cycle stealing DMA array signal processor for ultrasound sector imaging systems. *Microprocessors and Microsystems*, 64:53–72.

[KieŃczyński et  al., 2017] Kiełczyński, P., Ptasznik, S., Szalewski, M., Balcerzak, A., Wieja, K., and Rostocki, A. J. (2017). Thermophysical properties of rapeseed oil methyl esters (RME) at high pressures and various temperatures evaluated by ultrasonic methods. *Biomass and Bioenergy*, 107:113–121.

[Kim et  al., 2018] Kim, J. H., Yeo, S., Kim, J. W., Kim, K., Song, T.-K., Yoon, C., and Sung, J. (2018). Real-Time Lossless Compression Algorithm for Ultrasound Data Using BL Universal Code. *Sensors*, 18(10):3314.

[Kim et  al., 2017] Kim, J. H., Yeo, S., Kim, M., Kye, S., Lee, Y., and Song, T. k. (2017). A smart-phone based portable ultrasound imaging system for point-of-care applications. In *2017 10th International Congress on Image and Signal Processing, BioMedical Engineering and Informatics (CISP-BMEI)*, pages 1–5.

[Kim et  al., 2020] Kim, Y., Park, J., and Kim, H. (2020). Signal-Processing Framework for Ultrasound Compressed Sensing Data: Envelope Detection and Spectral Analysis. *Applied Sciences*, 10(19):6956.

[Kjeken et  al., 2011] Kjeken, I., Smedslund, G., Moe, R. H., Slatkowsky-Christensen, B., Uhlig, T., and Hagen, K. B. (2011). Systematic review of design and effects of splints and exercise programs in hand osteoarthritis. *Arthritis Care & Research*, 63(6):834–848.

[Kou et  al., 2020] Kou, Z., Miller, R. J., Singer, A. C., and Oelze, M. L. (2020). Real-time video streaming in vivo using ultrasound as the communication channel. *arXiv:2009.13683 [eess]*. arXiv: 2009.13683.

[Kruizinga et  al., 2017] Kruizinga, P., Meulen, P. v. d., Fedjajevs, A., Mastik, F., Springeling, G., Jong, N. d., Bosch, J. G., and Leus, G. (2017). Compressive 3D ultrasound imaging using a single sensor. *Science Advances*, 3(12):e1701423.

[Kurjak and Breyer, 1986] Kurjak, A. and Breyer, B. (1986). The use of ultrasound in developing countries. *Ultrasound in Medicine & Biology*, 12(8):611–621.

[Kuru et  al., 2019] Kuru, K., Ansell, D., Jones, M., Goede, C. D., and Leather, P. (2019). Feasibility study of intelligent autonomous determination of the bladder voiding need to treat bedwetting using ultrasound and smartphone ML techniques. *Medical & Biological Engineering & Computing*, 57(5):1079–1097.

[Kushi and Suresh  Babu, 2017] Kushi, A. and Suresh Babu, P. (2017). Ultrasonic Signal Processing Using FPGA. pages 82–87.

[Kwong et  al., 2020] Kwong, E., Ng, K.-W. K., Leung, M.-T., and Zheng, Y.-P. (2020). Application of Ultrasound Biofeedback to the Learning of the Mendelsohn Maneuver in Non-dysphagic Adults: A Pilot Study. *Dysphagia*.

[Lanza, 2020] Lanza, G. M. (2020). Ultrasound Imaging: Something Old or Something New? *Investigative Radiology*, 55(9):573–577.

[Lay et  al., 2018] Lay, H., Cummins, G., Cox, B. F., Qiu, Y., Turcanu, M. V., McPhillips, R., Connor, C., Gregson, R., Clutton, E., Desmulliez, M. P. Y., and Cochran, S. (2018). In-Vivo Evaluation of Microultrasound and Thermometric Capsule Endoscopes. *IEEE Transactions on Biomedical Engineering*, pages 1–1.

[Lay et  al., 2016] Lay, H. S., Qiu, Y., Al-Rawhani, M., Beeley, J., Poltarjonoks, R., Seetohul, V., Cumming, D., Cochran, S., Cummins, G., Desmulliez, M. P. Y., Wallace, M., Trolier-McKinstry, S., McPhillips, R., Cox, B. F., and Demore, C. E. M. (2016). Progress towards a multi-modal capsule endoscopy device featuring microultrasound imaging. In *2016 IEEE International Ultrasonics Symposium (IUS)*, pages 1–4. ISSN: 1948-5727.

[LeCoeur, ] LeCoeur. Bluetooth single channel ultrasonic device - Android systems.

[Lee et  al., 2014a] Lee, J. H., Traverso, G., Schoellhammer, C. M., Blankschtein, D., Langer, R., Thomenius, K. E., Boning, D. S., and Anthony, B. W. (2014a). Towards wireless capsule endoscopic ultrasound (WCEU). In *2014 IEEE International Ultrasonics Symposium*, pages 734–737, Chicago, IL, USA. IEEE.

[Lee et  al., 2014b] Lee, Y., Kang, J., Yeo, S., Lee, J., Kim, G. D., Yoo, Y., and Song, T. K. (2014b). A new smart probe system for a tablet PC-based point-of-care ultrasound imaging system: Feasibility study. In *2014 IEEE International Ultrasonics Symposium*, pages 1611–1614.

[Lei, ] Lei, S. A High-Frame Rate High-Frequency Ultrasonic System for Cardiac Imaging in Mice - IEEE Journals & Magazine.

[Lei Sun et  al., 2008] Lei Sun, Xiaochen Xu, Richard, W., Feng, C., Johnson, J., and Shung, K. (2008). A High-Frame Rate Duplex Ultrasound Biomicroscopy for Small Animal Imaging *In vivo*. *IEEE Transactions on Biomedical Engineering*, 55(8):2039–2049.

[Levesque and Sawan, 2009] Levesque, P. and Sawan, M. (2009). Real-Time Hand-Held Ultrasound Medical-Imaging Device Based on a New Digital Quadrature Demodulation Processor. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 56(8):1654–1665.

[Lewandowski et  al., 2012] Lewandowski, M., Sielewicz, K., and Walczak, M. (2012). A low-cost 32-channel module with high-speed digital interfaces for portable ultrasound systems. In *2012 IEEE International Ultrasonics Symposium*, pages 1–4, Dresden, Germany. IEEE.

[LI et  al., 2018] LI, H., LUO, L., GAO, X., and LI, J. (2018). Initial Architecture Design of Ultrasound Synthetic Aperture Imaging Based on FPGA. In *2018 IEEE Far East NDT New Technology Application Forum (FENDT)*, pages 60–64.

[Li et  al., 2014] Li, H., Zhou, Y., Wang, L., and Wen, X. (2014). A New Implementation of A-Mode Ultrasound Pulser-Receiver System. In *Modelling and Simulation 2014 5th International Conference on Intelligent Systems*, pages 187–190.

[Li et  al., 2016] Li, Y., He, K., Sun, X., and Liu, H. (2016). Human-machine interface based on multi-channel single-element ultrasound transducers: A preliminary study. In *2016 IEEE 18th International Conference on e-Health Networking, Applications and Services (Healthcom)*, pages 1–6.

[Liebgott et  al., 2012] Liebgott, H., Basarab, A., Kouame, D., Bernard, O., and Friboulet, D. (2012). Compressive sensing in medical ultrasound. In *2012 IEEE International Ultrasonics Symposium*, pages 1–6. ISSN: 1051-0117.

[Ligtvoet et  al., 1978] Ligtvoet, C., Rusterborgh, H., Kappen, L., and Bom, N. (1978). Real time ultrasonic imaging with a hand-held scanner Part I—Technical description. *Ultrasound in Medicine & Biology*, 4(2):91–92.

[Liutkus et  al., 2014] Liutkus, A., Martina, D., Popoff, S., Chardon, G., Katz, O., Lerosey, G., Gigan, S., Daudet, L., and Carron, I. (2014). Imaging With Nature: Compressive Imaging Using a Multiply Scattering Medium. *Scientific Reports*, 4:5552.

[Lorenzo et  al., 2009] Lorenzo, D. D., Momi, E. D., Beretta, E., Cerveri, P., Perona, F., and Ferrigno, G. (2009). Experimental validation of A-mode ultrasound acquisition system for computer assisted orthopaedic surgery. In *Medical Imaging 2009: Ultrasonic Imaging and Signal Processing*, volume 7265, page 726502. International Society for Optics and Photonics.

[Lukacs et  al., 1998] Lukacs, M., Sayer, M., and Foster, S. (1998). Single-element and linear-array transducer design for ultrasound biomicroscopy. In *Medical Imaging 1998: Ultrasonic Transducer Engineering*, volume 3341, pages 272–283. International Society for Optics and Photonics.

[Luong et  al., 2016] Luong, T.-D., Hies, T., and Ohl, C.-D. (2016). A compact time reversal emitter-receiver based on a leaky random cavity. *Scientific Reports*, 6:36096.

[Lévesque, 2011] Lévesque, P. (2011). *Architecture d’un processeur dédié aux traitements de signaux ultrasoniques en temps réel en vue d’une intégration sur puce*. phd.

[Martins, 2017] Martins, Y. W. (2017). A-scan ultrassônico aplicado na identificação da camada adiposa.

[Marwa et  al., 2019] Marwa, F., Youssef, W. E., Machhout, M., Petit, P., Baron, C., Guillermin, R., and Lasaygues, P. (2019). Automatic recognition processing in ultrasound computed tomography of bone. In *Medical Imaging 2019: Ultrasonic Imaging and Tomography*, volume 10955, page 1095514. International Society for Optics and Photonics.

[Matera et  al., 2018] Matera, R., Meacci, V., Rossi, S., Russo, D., Ricci, S., and Lootcns, D. (2018). Smart Ultrasound Sensor for Non-Destructive Tests. In *2018 New Generation of CAS (NGCAS)*, pages 29–32.

[Matzuk and Skolnick, 1978] Matzuk, T. and Skolnick, M. L. (1978). Novel ultrasonic real-time scanner featuring servo controlled transducers displaying a sector image. *Ultrasonics*, 16(4):171–178.

[Melde et  al., 2016] Melde, K., Mark, A. G., Qiu, T., and Fischer, P. (2016). Holograms for acoustics. *Nature*, 537(7621):518–522.

[Memon et  al., 2016] Memon, F., Touma, G., Wang, J., Baltsavias, S., Moini, A., Chang, C., Rasmussen, M. F., Nikoozadeh, A., Choe, J. W., Olcott, E., Jeffrey, R. B., Arbabian, A., and Khuri-Yakub, B. T. (2016). Capsule ultrasound device: Further developments. In *2016 IEEE International Ultrasonics Symposium (IUS)*, pages 1–4, Tours, France. IEEE.

[Meng, 2019] Meng, W. (2019). rtl-ultrasound: Ultrasound imaging with RTL-SDR.

[Montaldo et  al., 2004] Montaldo, G., Palacio, D., Tanter, M., and Fink, M. (2004). Time reversal kaleidoscope: A smart transducer for three-dimensional ultrasonic imaging. *Applied Physics Letters*, 84(19):3879–3881.

[Montaldo et  al., 2005] Montaldo, G., Palacio, D., Tanter, M., and Fink, M. (2005). Building three-dimensional images using a time-reversal chaotic cavity. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 52(9):1489–1497.

[Moradi et  al., 2006] Moradi, M., Abolmaesumi, P., Isotalo, P. A., Siemens, D. R., Sauerbrei, E. E., and Mousavi, P. (2006). Detection of Prostate Cancer from RF Ultrasound Echo Signals Using Fractal Analysis. In *2006 International Conference of the IEEE Engineering in Medicine and Biology Society*, pages 2400–2403. ISSN: 1557-170X.

[Moritz et  al., 2019] Moritz, M., Redlich, T., Günyar, S., Winter, L., and Wulfsberg, J. P. (2019). On the Economic Value of Open Source Hardware – Case Study of an Open Source Magnetic Resonance Imaging Scanner. *Journal of Open Hardware*, 3(1):2.

[Mostavi et  al., 2017] Mostavi, A., Tehrani, N., Kamali, N., Ozevin, D., Chi, S. W., and Indacochea, J. E. (2017). The application of water coupled nonlinear ultrasonics to quantify the dislocation density in aluminum 1100. *AIP Conference Proceedings*, 1806(1):060003.

[Nguyen et  al., 2019] Nguyen, T. T., Espinoza, A. W., Hyler, S., Remme, E. W., D’hooge, J., and Hoff, L. (2019). Estimating Regional Myocardial Contraction Using Miniature Transducers on the Epicardium. *Ultrasound in Medicine & Biology*, 45(11):2958–2969.

[Ni and Lee, 2020] Ni, P. and Lee, H.-N. (2020). High-Resolution Ultrasound Imaging Using Random Interference. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, pages 1–1.

[Nikolov et  al., 2008] Nikolov, S., Jensen, J., and Tomov, B. (2008). Fast parametric beamformer for synthetic aperture imaging. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 55(8):1755–1767.

[Nowak and Markowski, 2020] Nowak, K. W. and Markowski, M. (2020). Evaluation of selected properties of a gelatinized potato starch colloid by an ultrasonic method. *Measurement*, 158:107717.

[Ophir and Maklad, 1979] Ophir, J. and Maklad, N. (1979). Digital scan converters in diagnostic ultrasound imaging. *Proceedings of the IEEE*, 67(4):654–664.

[Ozdemir, 2018] Ozdemir, A. (2018). A Remote Tone Burst Pulser Design for Automated Ultrasonic Scanning Systems.

[Pandey and Vora, 2019] Pandey, G. and Vora, A. (2019). Open Electronics for Medical Devices: State-of-Art and Unique Advantages. *Electronics*, 8(11):1256.

[Park et  al., 2019] Park, D. W., Park, D. C., and Chung, S. H. (2019). Ultrasound Signal Processing Technique for Subcutaneous-Fat and Muscle Thicknesses Measurements. *IEEE Access*, 7:155203–155208. Conference Name: IEEE Access.

[Pashaei et  al., 2020] Pashaei, V., Dehghanzadeh, P., Enwia, G., Bayat, M., Majerus, S. J. A., and Mandal, S. (2020). Flexible Body-Conformal Ultrasound Patches for Image-Guided Neuromodulation. *IEEE Transactions on Biomedical Circuits and Systems*, 14(2):305–318. Conference Name: IEEE Transactions on Biomedical Circuits and Systems.

[Pashaei et  al., 2018] Pashaei, V., Roman, A., and Mandal, S. (2018). Live Demonstration: An Open-Source Test-Bench for Autonomous Ultrasound Imaging. pages 1–1.

[Pearce, 2015] Pearce, J. M. (2015). Quantifying the value of open source hardware development. *Modern Economy*, 6:1–11.

[Pearce, 2016] Pearce, J. M. (2016). Return on investment for open source scientific hardware development. *Science and Public Policy*, 43(2):192–195.

[Peyton et  al., 2017] Peyton, G., Boutelle, M., and M. Drakakis, E. (2017). Front-End Receiver Architecture for Miniaturised Ultrasound Imaging.

[Peyton et  al., 2018] Peyton, G., Boutelle, M. G., and Drakakis, E. M. (2018). Comparison of synthetic aperture architectures for miniaturised ultrasound imaging front-ends. *BioMedical Engineering OnLine*, 17:83.

[Poulsen et  al., 2005] Poulsen, C., Pedersen, P., and Szabo, T. (2005). An optical registration method for 3D ultrasound freehand scanning. In *Proceedings - IEEE Ultrasonics Symposium*, volume 2, pages 1236–1240.

[Pérez-Sánchez et  al., 2020] Pérez-Sánchez, A., Segura, J. A., Rubio-Gonzalez, C., Baldenegro-Pérez, L. A., and Soto-Cajiga, J. A. (2020). Numerical design and analysis of a langevin power ultrasonic transducer for acoustic cavitation generation. *Sensors and Actuators A: Physical*, 311:112035.

[Qiu et  al., 2018] Qiu, W., Xia, J., Shi, Y., Mu, P., Wang, X., Gao, M., Wang, C., Xiao, Y., Yang, G., Liu, J., Sun, L., and Zheng, H. (2018). A Delayed-Excitation Data Acquisition Method for High-Frequency Ultrasound Imaging. *IEEE transactions on bio-medical engineering*, 65(1):15–20.

[Qiu et  al., 2012] Qiu, W., Yu, Y., Chabok, H. R., Liu, C., Zhou, Q., Shung, K. K., Zheng, H., and Sun, L. (2012). A flexible annular array imaging platform for micro-ultrasound. In *2012 IEEE International Ultrasonics Symposium*, pages 2172–2175.

[Qiu et  al., 2010] Qiu, W., Yu, Y., and Sun, L. (2010). A programmable, cost-effective, real-time high frequency ultrasound imaging board based on high-speed FPGA. *Proceedings - IEEE Ultrasonics Symposium*, pages 1976–1979.

[Qiu et  al., 2011] Qiu, W., Yu, Y., Tsang, F. K., and Sun, L. (2011). A programmable and compact open platform for ultrasound bio-microscope. In *2011 IEEE International Ultrasonics Symposium*, pages 1048–1051.

[Qiu and Zheng, 2020] Qiu, W. and Zheng, H. (2020). High-Resolution Ultrasound Imaging System. In Zhou, Q. and Chen, Z., editors, *Multimodality Imaging: For Intravascular Application*, pages 257–273. Springer, Singapore.

[Qiu et  al., 2020] Qiu, Y., Huang, Y., Zhang, Z., Cox, B. F., Liu, R., Hong, J., Mu, P., Lay, H. S., Cummins, G., Desmulliez, M. P. Y., Clutton, E., Zheng, H., Qiu, W., and Cochran, S. (2020). Ultrasound Capsule Endoscopy With a Mechanically Scanning Micro-ultrasound: A Porcine Study. *Ultrasound in Medicine & Biology*, 46(3):796–804.

[Rabut et  al., 2019] Rabut, C., Correia, M., Finel, V., Pezet, S., Pernot, M., Deffieux, T., and Tanter, M. (2019). 4D functional ultrasound imaging of whole-brain activity in rodents. *Nature Methods*, 16(10):994–997.

[Raj et  al., 2016] Raj, J., Smk, R., and Anand, S. (2016). *8051 microcontroller to FPGA and ADC interface design for high speed parallel processing systems – Application in ultrasound scanners*, volume 19.

[Raj et  al., 2018] Raj, J. J. R., Rahman, S., and Anand, S. (2018). Programmable FPGA-based 32-channel transmitter for high frame rate ultrasound channel excitation applications. *International Journal of Instrumentation Technology*, 2(1):18–33.

[Raj et  al., 2017] Raj, J. R., Rahman, S. M. K., and Anand, S. (2017). Microcontroller USB interfacing with MATLAB GUI for low cost medical ultrasound scanners. *Collection of Engineering Science and Technology, an International Journal*.

[Ranachowski et  al., 2020] Ranachowski, Z., Ranachowski, P., Dębowski, T., Brodecki, A., Kopec, M., Roskosz, M., Fryczowski, K., Szymków, M., Krawczyk, E., and Schabowicz, K. (2020). Mechanical and Non-Destructive Testing of Plasterboards Subjected to a Hydration Process. *Materials*, 13(10):2405.

[Ratajski and Trajer, 2017] Ratajski, A. and Trajer, J. (2017). Application of ultrasounds to determine carrot juice properties. *Annals of Warsaw University of Life Sciences - SGGW - Agriculture (Agricultural and Forest Engineering)*, 70:143–147.

[Rathod, 2019] Rathod, V. T. (2019). A Review of Electric Impedance Matching Techniques for Piezoelectric Sensors, Actuators and Transducers. *Electronics*, 8(2):169.

[Ricci et  al., 2006] Ricci, S., Boni, E., Guidi, F., Morganti, T., and Tortoli, P. (2006). A programmable real-time system for development and test of new ultrasound investigation methods. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 53(10):1813–1819.

[Richard et  al., 2008] Richard, W. D., Zar, D. M., and Solek, R. (2008). A low-cost B-mode USB ultrasound probe. *Ultrasonic Imaging*, 30(1):21–28.

[Rodrí guez-Olivares et  al., 2018] Rodríguez-Olivares, N., Cruz-Cruz, J., Gómez-Hernández, A., Hernández-Alvarado, R., Nava-Balanzar, L., Salgado-Jiménez, T., and Soto-Cajiga, J. (2018). Improvement of Ultrasonic Pulse Generator for Automatic Pipeline Inspection. *Sensors*, 18(9):2950.

[Roman, 2019] Roman, A. (2019). *Open-Source Test-Bench Design for Applications in Autonomous. Ultrasound Imaging.* PhD thesis, CASE WESTERN RESERVE UNIVERSITY.

[Roman et  al., 2018] Roman, A., Dehghanzadeh, P., Pashaei, V., Basak, A., Bhunia, S., and Mandal, S. (2018). An Open-Source Test-Bench for Autonomous Ultrasound Imaging. In *2018 IEEE 61st International Midwest Symposium on Circuits and Systems (MWSCAS)*, pages 524–527, Windsor, ON, Canada. IEEE.

[Romero-Laorden et  al., 2013] Romero-Laorden, D., Villazn-Terrazas, J., Martnez-Graullera, O., and Ibez, A. (2013). Strategies for Hardware Reduction on the Design of Portable Ultrasound Imaging Systems. In Gunarathne, G. P. P., editor, *Advancements and Breakthroughs in Ultrasound Imaging*. InTech.

[Rymarczyk et  al., 2019] Rymarczyk, T., Kozłowski, E., Kłosowski, G., and Niderla, K. (2019). Logistic Regression for Machine Learning in Process Tomography. *Sensors*, 19(15):3400. Number: 15 Publisher: Multidisciplinary Digital Publishing Institute.

[Sabbella, 2021] Sabbella, H. (2021). Dhvani project.

[Saijo, ] Saijo, Y. Development of an ultra-portable echo device connected to USB port. - PubMed - NCBI. 10.1016/j.ultras.2003.11.009.

[Saiz-Vela et  al., 2020] Saiz-Vela, A., Fontova, P., Pallejá, T., Tresanchez, M., Garriga, J. A., and Roig, C. (2020). A low-cost development platform to design digital circuits on FPGAs using open-source software and hardware tools. In *2020 XIV Technologies Applied to Electronics Teaching Conference (TAEE)*, pages 1–8.

[Santagati et  al., 2020] Santagati, G. E., Dave, N., and Melodia, T. (2020). Design and Performance Evaluation of an Implantable Ultrasonic Networking Platform for the Internet of Medical Things. *IEEE/ACM Transactions on Networking*, 28(1):29–42.

[Sarvazyan et  al., 2009] Sarvazyan, A. P., Fillinger, L., and Gavrilov, L. R. (2009). A comparative study of systems used for dynamic focusing of ultrasound. *Acoustical Physics*, 55(4-5):630–637.

[Schneider et  al., 2010] Schneider, F. K., Agarwal, A., Yoo, Y. M., Fukuoka, T., and Kim, Y. (2010). A Fully Programmable Computing Architecture for Medical Ultrasound Machines. *IEEE Transactions on Information Technology in Biomedicine*, 14(2):538–540.

[Scholle and Sinapius, 2018] Scholle, P. and Sinapius, M. (2018). Pulse Ultrasonic Cure Monitoring of the Pultrusion Process. *Sensors*, 18(10):3332. Number: 10 Publisher: Multidisciplinary Digital Publishing Institute.

[Schueler et  al., 1984] Schueler, C. F., Lee, H., and Wade, G. (1984). Fundamentals of Digital Ultrasonic Processing. *IEEE Transactions on Sonics and Ultrasonics*, 31(4):195–217.

[Schuette et  al., 1976] Schuette, W. H., Norris, G. F., and Doppman, J. L. (1976). Real Time Two-Dimensional Mechanical Ultrasonic Sector Scanner With Electronic Control Of Sector Width. In *Application of Optical Instrumentation in Medicine V*, volume 0096, pages 345–348. International Society for Optics and Photonics.

[Seo et  al., 2016] Seo, D., Neely, R. M., Shen, K., Singhal, U., Alon, E., Rabaey, J. M., Carmena, J. M., and Maharbiz, M. M. (2016). Wireless Recording in the Peripheral Nervous System with Ultrasonic Neural Dust. *Neuron*, 91(3):529–539. Publisher: Elsevier.

[Seo, 2018] Seo, J. (2018). *A non-invasive central arterial pressure waveform estimation system using ultrasonography for real-time monitoring*. Thesis, Massachusetts Institute of Technology.

[Shah et  al., 2019] Shah, D., Hung, E., Wolf, C., Bazanski, S., Gisselquist, D., and Milanovic, M. (2019). Yosys+nextpnr: An Open Source Framework from Verilog to Bitstream for Commercial FPGAs. In *2019 IEEE 27th Annual International Symposium on Field-Programmable Custom Computing Machines (FCCM)*, pages 1–4. ISSN: 2576-2613.

[Shahshahani et  al., 2018] Shahshahani, A., Laverdiere, C., Bhadra, S., Zilic, Z., Shahshahani, A., Laverdiere, C., Bhadra, S., and Zilic, Z. (2018). Ultrasound Sensors for Diaphragm Motion Tracking: An Application in Non-Invasive Respiratory Monitoring. *Sensors*, 18(8):2617.

[Sharma, 2015] Sharma, J. K. (2015). Development of a wide band front end echo sounder receiver circuit.

[Shaw, 1977] Shaw, A. (1977). Mechanical sector scanners. In Bom, N., editor, *Echocardiology: with Doppler applications and Real time imaging*, pages 305–311. Springer Netherlands, Dordrecht.

[Shomaji et  al., 2019] Shomaji, S., Dehghanzadeh, P., Roman, A., Forte, D., Bhunia, S., and Mandal, S. (2019). Early Detection of Cardiovascular Diseases Using Wearable Ultrasound Device. *IEEE Consumer Electronics Magazine*, 8(6):12–21.

[Sikdar et  al., 2014] Sikdar, S., Rangwala, H., Eastlake, E. B., Hunt, I. A., Nelson, A. J., Devanathan, J., Shin, A., and Pancrazio, J. J. (2014). Novel Method for Predicting Dexterous Individual Finger Movements by Imaging Muscle Activity Using a Wearable Ultrasonic System. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 22(1):69–76.

[Skolnick and Matzuk, 1978] Skolnick, M. L. and Matzuk, T. (1978). A new ultrasonic real-time scanner featuring a servo-controlled transducer displaying a sector image. *Radiology*, 128(2):439–445.

[Smith et  al., 2015] Smith, K. J., Graham, D. J., and Neasham, J. A. (2015). Design and Optimization of a Voice Coil Motor With a Rotary Actuator for an Ultrasound Scanner. *IEEE Transactions on Industrial Electronics*, 62(11):7073–7078.

[Sobhani et  al., 2016] Sobhani, M. R., Ozum, H. E., Yaralioglu, G. G., Ergun, A. S., and Bozkurt, A. (2016). Portable low cost ultrasound imaging system. In *2016 IEEE International Ultrasonics Symposium (IUS)*, pages 1–4.

[Sosnowska et  al., 2019] Sosnowska, A., Vuckovic, A., and Gollee, H. (2019). Training Towards Precise Control Over Muscle Activity with Real Time Biofeedback Based on Ultrasound Imaging. *World Congress on Medical Physics and Biomedical Engineering 2018*, pages 49–52.

[Soto-Cajiga et  al., 2012] Soto-Cajiga, J. A., Pedraza-Ortega, J. C., Rubio-Gonzalez, C., Bandala-Sanchez, M., and Romero-Troncoso, R. d. J. (2012). FPGA-based architecture for real-time data reduction of ultrasound signals. *Ultrasonics*, 52(2):230–237.

[Sun et  al., 2018] Sun, X. L., Yan, J. P., Li, Y. F., and Liu, H. (2018). Multi-frequency ultrasound transducers for medical applications: a survey. *International Journal of Intelligent Robotics and Applications*, 2(3):296–312.

[Svilainis et  al., 2014] Svilainis, L., Dumbrava, V., Kitov, S., Aleksandrovas, A., Tervydis, P., and Liaukonis, D. (2014). Electronics for Ultrasonic Imaging System. *Elektronika ir Elektrotechnika*, 20:51–56.

[Tang and Clement, 2014] Tang, S. C. and Clement, G. (2014). A computerized tomography system for transcranial ultrasound imaging. *Proceedings of Meetings on Acoustics*, 22(1):020001.

[Taylor et  al., 2017] Taylor, Z. D., Jonveaux, L., and Caskey, C. T. (2017). Development of a Portable and Inexpensive Ultrasound Imaging Device for Use in the Developing World.

[Techavipoo et  al., 2012] Techavipoo, U., Keinprasit, R., Pinunsottikul, P., Jewajinda, Y., Punyasai, C., Thajchayapong, P., Siritan, T., and Worasawate, D. (2012). An ultrasound imaging system prototype for raw data acquisition. In *The 5th 2012 Biomedical Engineering International Conference*, pages 1–4.

[Tortoli et  al., 2009] Tortoli, P., Bassi, L., Boni, E., Dallai, A., Guidi, F., and Ricci, S. (2009). ULA-OP: an advanced open platform for ultrasound research. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 56(10):2207–2216.

[Triger et  al., 2008] Triger, S., Wallace, J., Wang, L., Cumming, D. R. S., Saillant, J.-F., Afroukh, F., and Cochran, S. (2008). A modular FPGA-based ultrasonic array system for applications including non-destructive testing.

[Vadalma, 2020] Vadalma, A. (2020). *Smartphone ultrasound imaging*. Master of Philosophy, Queensland University of Technology.

[van  der Meulen et  al., 2017] van der Meulen, P., Kruizinga, P., Bosch, J. G., and Leus, G. (2017). Spatial compression in ultrasound imaging. In *2017 51st Asilomar Conference on Signals, Systems, and Computers*, pages 1016–1020, Pacific Grove, CA, USA. IEEE.

[Vasudevan et  al., 2014] Vasudevan, V., Govindan, P., and Saniie, J. (2014). Programmable analog front-end system for ultrasonic SoC hardware. In *IEEE International Conference on Electro/Information Technology*, pages 356–361.

[Veenstra, ] Veenstra, V. Generating high frame rate MR images using surrogate signals | Robotics and Mechatronics.

[Vogt and Ermert, 2005] Vogt, M. and Ermert, H. (2005). Development and evaluation of a high-frequency ultrasound-based system for in vivo strain imaging of the skin. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 52(3):375–385.

[Wahab et  al., 2016] Wahab, M. A. A., Sudirman, R., Omar, C., and Ariffin, I. (2016). Design of an A-mode ultrasound amplifier for bone porosity detection. In *2016 International Symposium on Electronics and Smart Devices (ISESD)*, pages 79–84.

[Wall, 2010] Wall, K. (2010). *A High-Speed Reconfigurable System for Ultrasound Research*. Thesis.

[Wang and Saniie, 2019] Wang, B. and Saniie, J. (2019). A High Performance Ultrasonic System for Flaw Detection. In *2019 IEEE International Ultrasonics Symposium (IUS)*, pages 840–843. ISSN: 1948-5727.

[Wang et  al., 2019a] Wang, R., Fang, Z., Gu, J., Guo, Y., Zhou, S., Wang, Y., Chang, C., and Yu, J. (2019a). High-resolution image reconstruction for portable ultrasound imaging devices. *EURASIP Journal on Advances in Signal Processing*, 2019(1):56.

[Wang et  al., 2020] Wang, S., Hossack, J. A., and Klibanov, A. L. (2020). From Anatomy to Functional and Molecular Biomarker Imaging and Therapy: Ultrasound Is Safe, Ultrafast, Portable, and Inexpensive. *Investigative Radiology*, 55(9):559–572.

[Wang et  al., 2019b] Wang, X., He, C., Xie, W., and Hu, H. (2019b). Preliminary Research on the Nonlinear Ultrasonic Detection of the Porosity of Porous Material Based on Dynamic Wavelet Fingerprint Technology. *Sensors*, 19(15):3328. Number: 15 Publisher: Multidisciplinary Digital Publishing Institute.

[Wang et  al., 2017] Wang, X., Seetohul, V., Chen, R., Zhang, Z., Qian, M., Shi, Z., Yang, G., Mu, P., Wang, C., Huang, Z., Zhou, Q., Zheng, H., Cochran, S., and Qiu, W. (2017). Development of a Mechanical Scanning Device With High-Frequency Ultrasound Transducer for Ultrasonic Capsule Endoscopy. *IEEE Transactions on Medical Imaging*, 36(9):1922–1929.

[Wang et  al., 2021] Wang, X., Yang, J., Ji, J., Zhang, Y., and Zhou, S. (2021). Research on Golay-coded excitation in real-time imaging of high frequency ultrasound biomicroscopy. *Scientific Reports*, 11(1):1848.

[Warner et  al., 2013] Warner, M., Ratcliffe, A., Nangoo, T., Morgan, J., Umpleby, A., Shah, N., Vinje, V., Štekl, I., Guasch, L., Win, C., Conroy, G., and Bertrand, A. (2013). Anisotropic 3D full-waveform inversion. *Geophysics*, 78(2).

[Wei et  al., 2020] Wei, C., Chen, H., and Chen, Y. (2020). Design of an automatic impedance matching circuit based on frequency tracking of ultrasonic transducer. In *2020 IEEE 5th Information Technology and Mechatronics Engineering Conference (ITOEC)*, pages 162–165.

[Wen et  al., 2019] Wen, L., Tan, C., Dong, F., and Zhao, S. (2019). Design of Ultrasonic Tomography System for Biomedical Imaging. In *2019 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, pages 1–5.

[Weng et  al., 2015] Weng, C.-K., Chen, J.-W., and Huang, C.-C. (2015). A FPGA-based wearable ultrasound device for monitoring obstructive sleep apnea syndrome. pages 1–4. IEEE.

[Wilkinson, 1981] Wilkinson, R. W. (1981). Principles of real-time two-dimensional B-scan ultrasonic imaging. *Journal of Medical Engineering & Technology*, 5(1):21–29.

[Winter et  al., 2019] Winter, L., Pellicer-Guridi, R., Broche, L., Winkler, S. A., Reimann, H. M., Han, H., Arndt, F., Hodge, R., Günyar, S., Moritz, M., Ettinger, K. M., de Fresnoye, O., Niendorf, T., and Benchoufi, M. (2019). Open Source Medical Devices for Innovation, Education and Global Health: Case Study of Open Source Magnetic Resonance Imaging. In Redlich, T., Moritz, M., and Wulfsberg, J. P., editors,  *Co-Creation: Reshaping Business and Society in the Era of Bottom-up Economics*, Management for Professionals, pages 147–163. Springer International Publishing, Cham.

[Worthing, 2016] Worthing, R. T. (2016). *Using ultrasound to measure arterial diameter for the development of a wearable blood pressure monitoring*. PhD thesis. 10.14288/1.0320796.

[Wu et  al., 2013] Wu, J.-X., Du, Y.-C., Lin, C.-H., Chen, P.-J., and Chen, T. (2013). A novel bipolar pulse generator for high-frequency ultrasound system. In *2013 IEEE International Ultrasonics Symposium (IUS)*, pages 1571–1574.

[Xiao et  al., 2013] Xiao, D., Shao, J., Ren, H., and Xu, C. (2013). Design of a high voltage pulse circuit for exciting ultrasonic transducers. In *2013 Far East Forum on Nondestructive Evaluation/Testing: New Technology and Application*, pages 224–230.

[Xu et  al., 2019] Xu, K., Kim, Y., Boctor, E. M., and Zhang, H. K. (2019). Enabling low-cost point-of-care ultrasound imaging system using single element transducer and delta configuration actuator. In *Medical Imaging 2019: Image-Guided Procedures, Robotic Interventions, and Modeling*, volume 10951, page 109510W. International Society for Optics and Photonics.

[Xu et  al., 2008] Xu, X., Sun, L., Cannata, J. M., Yen, J. T., and Shung, K. K. (2008). High-frequency Ultrasound Doppler System for Biomedical Applications with a 30 MHz Linear Array. *Ultrasound in medicine & biology*, 34(4):638–646.

[Xu et  al., 2010] Xu, X., Venkataraman, H., Oswal, S., Bartolome, E., and Vasanth, K. (2010). Challenges and considerations of analog front-ends design for portable ultrasound systems. In *2010 IEEE International Ultrasonics Symposium*, pages 310–313. ISSN: 1948-5719.

[Xu et  al., 2007] Xu, X., Yen, J. T., and Shung, K. K. (2007). A low-cost bipolar pulse generator for high-frequency ultrasound applications. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 54(2):443–447.

[Yang et  al., 2009] Yang, D., Li, H., Peterson, G. D., and Fathy, A. (2009). Compressed sensing based UWB receiver: Hardware compressing and FPGA reconstruction. pages 198–201. IEEE.

[Yang et  al., 2019] Yang, X., Chen, Z., Hettiarachchi, N., Yan, J., and Liu, H. (2019). A Wearable Ultrasound System for Sensing Muscular Morphological Deformations. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, pages 1–10.

[Yang et  al., 2020] Yang, X., Yan, J., Fang, Y., Zhou, D., and Liu, H. (2020). Simultaneous Prediction of Wrist/Hand Motion via Wearable Ultrasound Sensing. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 28(4):970–977.

[Yang et  al., 2021] Yang, Y., Wright, W. M. D., Hettinga, K. A., and van Ruth, S. M. (2021). Exploration of an ultrasonic pulse echo system for comparison of milks, creams, and their dilutions. *LWT*, 136:110616.

[Ylitalo and Ermert, 1994] Ylitalo, J. T. and Ermert, H. (1994). Ultrasound synthetic aperture imaging: monostatic approach. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 41(3):333–339.

[Yu et  al., 2020] Yu, H., Kim, J., Kim, H., Barange, N., Jiang, X., and So, F. (2020). Direct Acoustic Imaging Using a Piezoelectric Organic Light-Emitting Diode. *ACS Applied Materials & Interfaces*, 12(32):36409–36416.

[Zeiss, 1962] Zeiss, C. (1962). Sonovisor 2. *Journal of Scientific Instruments*, 39(10):538–538.

[Zhang et  al., 2019a] Zhang, D., Watson, R., Dobie, G., MacLeod, C., Lines, D., Galbraith, W., Mineo, C., and Pierce, G. (2019a). Evaluation of coded excitations for autonomous airborne ultrasonic inspection.

[Zhang et  al., 2018a] Zhang, D., Watson, R., Dobie, G., MacLeod, C., and Pierce, G. (2018a). Autonomous Ultrasonic Inspection Using Unmanned Aerial Vehicle. In *2018 IEEE International Ultrasonics Symposium (IUS)*, pages 1–4. ISSN: 1948-5727.

[Zhang et  al., 2021] Zhang, D., Watson, R., MacLeod, C., Dobie, G., Galbraith, W., and Pierce, G. (2021). Implementation and evaluation of an autonomous airborne ultrasound inspection system. *Nondestructive Testing and Evaluation*, 0(0):1–21.

[Zhang et  al., 2017] Zhang, D.-l., Yang, C., Jian, X.-h., Zhang, Q., and Cui, Y.-y. (2017). A multi-channel a-scan ultrasound system for real-time, non-invasive study of carotid artery compliance. In *2017 Symposium on Piezoelectricity, Acoustic Waves, and Device Applications (SPAWDA)*, pages 486–489. ISSN: null.

[Zhang et  al., 2016] Zhang, H. K., Cheng, A., Bottenus, N., Guo, X., Trahey, G. E., and Boctor, E. M. (2016). Synthetic tracked aperture ultrasound imaging: design, simulation, and experimental evaluation. *Journal of Medical Imaging*, 3(2):027001.

[Zhang et  al., 2018b] Zhang, H. K., Kim, Y., Lin, M., Paredes, M., Kannan, K., Moghekar, A., Durr, N. J., and Boctor, E. M. (2018b). Toward dynamic lumbar puncture guidance using needle-based single-element ultrasound imaging. *Journal of Medical Imaging*, 5(02):1.

[Zhang, 2012] Zhang, L. (2012). *FPGA embedded system for ultrasonic non-destructive testing*. Thesis, Brunel University London.

[Zhang et  al., 2019b] Zhang, Q., Song, J., Zhou, L., Peng, Y., Zhou, Q., Wang, S., Sun, X., Ding, M., and Yuchi, M. (2019b). A high throughout, extensible and flexible ultrasonic excitation and acquisition system for ultrasound imaging. In *Medical Imaging 2019: Ultrasonic Imaging and Tomography*, volume 10955, page 109550L. International Society for Optics and Photonics.

[Zhang et  al., 2019c] Zhang, W.-T., Lin, Y.-C., Chen, W.-H., Yang, C.-W., and Chiang, H.-H. K. (2019c). A Free-Hand System of the High-Frequency Single Element Ultrasound Transducer for Skin Imaging. In *Future Trends in Biomedical and Health Informatics and Cybersecurity in Medical Devices*, pages 91–99. Springer, Cham.

[Zhang, 2015] Zhang, X. (2015). *Design of a single element 3D ultrasound scanner*. Thesis, Massachusetts Institute of Technology.

[Zhang et  al., 2019d] Zhang, X., Fincke, J. R., Wynn, C. M., Johnson, M. R., Haupt, R. W., and Anthony, B. W. (2019d). Full noncontact laser ultrasound: first human data. *Light: Science & Applications*, 8(1):119.

[Zimmermann, 2018a] Zimmermann, H. (2018a). High Frequency 1-Ch System.

[Zimmermann, 2018b] Zimmermann, H. (2018b). Miniaturized Multi-Channel System.

[Zimmermann, 2019] Zimmermann, H. (2019). Highly Miniaturized 8-Ch System.

1. Lead of the un0rick.cc project [↑](#footnote-ref-3)